PB81-111049

Ultraviolet Disinfection of Municipal Wastewater Effluents

Dallas City Water Utilities Dept., TX

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Aug 80

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/2-80-102

2.

3. RECIPIENT'S ACCESSION NO.
PB81 111049

4. TITLE AND SUBTITLE
ULTRAVIOLET DISINFECTION OF MUNICIPAL
WASTEWATER EFFLUENTS

5. REPORT DATE
August 1980 (Issuing Date)

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Albert C. Petrasek, Jr., Harold W. Wolf,
Steven E. Esmond, and D. Craig Andrews

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Dallas Water Utilities
Dallas, Texas 75201

10. PROGRAM ELEMENT NO.
35B1C, D.U. B-124, Task A/06

11. CONTRACT/GRANT NO.
Grant #R-803292

12. SPONSORING AGENCY NAME AND ADDRESS
Municipal Environmental Research Laboratory--Cin.,OH
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED
Final, 6/74-8/76

14. SPONSORING AGENCY CODE
EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer: Albert D. Venosa (513) 684-7668

16. ABSTRACT

During this project two different UV exposure and irradiation systems were studied. The first system investigated was the Kelly-Purdy Unit, which consisted of a shallow-tray exposure chamber with 13 UV lamps mounted horizontally 10 cm above the bottom of the chamber. This unit was operated under varying conditions of both flow and depth and generally provided inadequate disinfection, although fecal coliform densities were usually reduced by approximately three logs.

The second UV system used during the project was the Model EP-50 manufactured by Ultraviolet Purification Systems, Inc. This exposure chamber consisted of a stainless steel pressure vessel with nine UV lamps running longitudinally through the chamber. Each lamp was isolated from the effluent being disinfected by a quartz sleeve. The disinfection observed on any given run was shown to be a function of the UV dose, and greater than four log reductions in fecal coliform densities were observed at times.

During this project three special virus studies were conducted. The influent to the EP-50 was seeded with an F2 coliphage and an attenuated Type I poliovirus. During the three virus runs, viral and phage densities in the influent and effluent of the UV irradiation chamber were monitored. The observed reductions in viruses were correlated with UV doses, and the F2 coliphage response to the UV disinfection process was similar to the response of the Type I poliovirus.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Disinfection Ultraviolet radiation Coliform bacteria Wastewater, waste, treatment Microorganism control, bactericides	Dallas, TX; UV absorbance; Wastewater quality; Nitrified effluent; Viruses; Poliovirus; Bacteriophage	13B

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980--657-146/[illegible]

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-80-102
August 1980

Research and Development

PB81-111049

EPA

Ultraviolet Disinfection of Municipal Wastewater Effluents

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/2-80-102
August 1980

ULTRAVIOLET DISINFECTION OF MUNICIPAL WASTEWATER EFFLUENTS

by

Albert C. Petrasek, Jr.
Harold W. Wolf
Steven E. Esmond
D. Craig Andrews

Texas A & M University
College Station, Texas 77843

Grant No. R-803292

Project Officer

Albert D. Venosa
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

18

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This study concerns the evaluation of ultraviolet light as a potential candidate for replacing chlorine as a wastewater effluent disinfectant. Development of a process such as ultraviolet light disinfection is important, since it is nontoxic to aquatic life, does not form potentially toxic halogenated compounds in the treated water, and provides excellent disinfection at a reasonable cost.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This research project was conducted at the Dallas Water Reclamation Research Center by the Dallas Water Utilities Department, Texas A&M University, and the United States Environmental Protection Agency to evaluate the feasibility of using ultraviolet light irradiation as a disinfection process for municipal wastewater effluents.

During this project two different UV exposure and irradiation systems were studied. The first system investigated was the Kelly-Purdy Unit, which consisted of a shallow-tray exposure chamber with 13 UV lamps mounted horizontally 10 cm above the bottom of the chamber. This unit was operated under varying conditions of both flow and depth and generally provided inadequate disinfection, although fecal coliform densities were usually reduced by approximately three logs.

The second UV system used during the project was the Model EP-50 manufactured by Ultraviolet Purification Systems, Inc. This exposure chamber consisted of a stainless steel pressure vessel with nine UV lamps running longitudinally through the chamber. Each lamp was isolated from the effluent being disinfected by a quartz sleeve. The disinfection observed on any given run was shown to be a function of the UV dose, and greater than four log reductions in fecal coliform densities were observed at times.

During this project three special virus studies were conducted. The influent to the EP-50 was seeded with an F2 coliphage and an attenuated Type I poliovirus. During the three virus runs, viral and phage densities in the influent and effluent of the UV irradiation chamber were monitored. The observed reductions in viruses were correlated with UV doses, and the F2 coliphage response to the UV disinfection process was similar to the response of the Type I poliovirus.

This report was submitted in fulfillment of Grant No. R-803292 by Dallas Water Utilities under the sponsorship of the U.S. Environmental Protection Agency.

CONTENTS

Foreword iii

Abstract iv

Figures vii

Tables xv

Acknowledgment xix

1. Introduction 1
    Background of the Dallas program 4
    Research presented in this report 5

2. Conclusions 7

3. Recommendations . . . .

4. Description of Research Facilities 11
    City of Dallas collection system 11
    Treatment facilities 14

5. Sampling and Analytical Procedures 29
    Sampling procedures 29
    Analytical procedures 29

6. Operation of the Kelly-Purdy Unit 34
    Hydraulic characteristics 34
    Intensity and dose determinations 38
    Run No. K1 49
    Run No. K2 53
    Run No. K3 65
    Run No. K4 75
    Run No. K5 82

7. Operation of the UPS Unit 96
    Hydraulic characteristics 96
    Determination of dose 103
    Run No. U1 109
    Run No. U2 119

CONTENTS (continued)

Run No. U3 119
Run No. U4 130
Run No. U5 140
Run No. U6 158
Run No. U7 167
Run No. U8 174

8. Virus Studies 191
First UV virus run 193
Second UV virus run 199
Third UV virus run 213

9. Summary of Operating Experience 230

10. Photoreactivation 252

References. 260

FIGURES

Number Page

1 Existing City of Dallas water supply network 2

2 Possible sources of influents for the Pilot Plant at the White Rock Sewage Treatment Plant 17

3 Flow schematic of the Dallas Water Reclamation Research Center Demonstration Plant 18

4 Perspective drawing of the Kelly-Purdy unit 26

5 Theoretical residence time as a function of flow and depth for the Kelly-Purdy system 35

6 Residence time distribution functions obtained at a water depth of 2.54 cm in the Kelly-Purdy system 36

7 Residence time distribution functions obtained at a depth of 6.35 cm in the Kelly-Purdy system 37

8 Ratio of actual to theoretical residence time for the Kelly-Purdy unit as a function of flow 39

9 Dimensionless, cumulative residence time distribution function for the Kelly-Purdy unit (2.54 cm water depth). 40

10 Dimensionless, cumulative residence time distribution function for the Kelly-Purdy unit (6.35 cm water depth). 41

11 Measured UV light intensities at various locations in the Kelly-Purdy irradiation chamber. 42

12 Average intensity of UV light as a function of water depth and the extinction coefficient 44

13 Typical data used to determine the extinction coefficient 45

14 Comparison between the observed and theoretically predicted relationship of the extinction coefficient and transmittance 47

FIGURES (continued)

Number Page

15 UV dose as a function of flow and the extinction coefficient for the Kelly-Purdy unit 48

16 Demonstration Plant configuration during Run No. K1, August 6, 1974 50

17 Results of Run No. K1, August 6, 1974 52

18 Pilot Plant configuration for Run No. K2 54

19 Standard plate count data for Run No. K2 58

20 Total coliform data for Run No. K2 59

21 Fecal coliform data for Run No. K2 21

22 Extreme-value frequency distribution for standard plate count data, Run No. K2 62

23 Extreme-value frequency distribution for total coliform data, Run No. K2 63

24 Extreme-value frequency distribution for fecal coliform data, Run No. K2 64

25 Pilot Plant process configuration during Run No. K3 . . . 25

26 Standard plate count data for Run No. K3 69

27 Total coliform data for Run No. K3 70

28 Fecal coliform data for Run No. K3 28

29 Extreme-value frequency distribution for standard plate count data, Run No. K3 72

30 Extreme-value frequency distribution for total coliforms, Run No. K3 73

31 Extreme-value frequency distribution for fecal coliform data, Run No. K3 74

32 Pilot Plant process configuration during Run No. K4 . . . 76

33 Standard plate count data for Run No. K4 79

34 Total coliform data for Run No. K4 80

FIGURES (continued)

Number Page

35 Fecal coliform data for Run No. K4 81

36 Extreme-value frequency distribution for standard plate count data, Run No. K4 83

37 Extreme-value frequency distribution for total coliform data, Run No. K4 84

38 Extreme-value frequency distribution for fecal coliform data, Run No. K4 85

39 Pilot Plant configuration during Run No. K5 86

40 Standard plate count data for Run No. K5 89

41 Total coliform data for Run No. K5 90

42 Fecal coliform data for Run No. K5 91

43 Extreme-value frequency distribution for standard plate count data, Run No. K5 93

44 Extreme-value frequency distribution for total coliform data, Run No. K5 94

45 Extreme-value frequency distribution for fecal coliform data, Run No. K5 95

46 Schematic flow diagram of UV light system 97

47 Theoretical residence time of UPS UV disinfection unit as a function of liquid flow rate 98

48 RTDF's for the UPS UV unit at 0.63 liters/sec. 99

49 RTDF for UPS unit at 1.89 liters/sec 100

50 RTDF's for the UPS unit at 3.47 liters/sec 101

51 Cummulative dimensionless RTDF's for the UPS unit 102

52 Isointensity patterns for UPS exposure chamber 105

53 The effect of flow and extinction coefficient on the calculated UV dose 108

54 Pilot Plant configuration during Run No. U1 110

FIGURES (continued)

Number | | Page
55 Standard plate count data for Run No. U1 113

56 Total coliform data for Run No. U1 114

57 Fecal coliform data for Run No. U1 115

58 Extreme-value frequency distribution of standard plate count data for Run No. U1. 116

59 Extreme-value frequency distribution of total coliform data for Run No. U1. 117

60 Extreme-value frequency distribution of fecal coliform data for Run No. U1. 118

61 Pilot Plant configuration during Run No. U2 120

62 Standard plate count data for Run No. U2 123

63 Total coliform data for Run No. U2 124

64 Fecal coliform data for Run No. U2 125

65 Extreme-value frequency distribution of standard plate count data for Run No. U2 126

66 Extreme-value frequency distribution of total coliform data for Run No. U2 127

67 Extreme-value frequency distribution of fecal coliform data for Run No. U2 128

68 Pilot Plant process configuration for Run No. U3 129

69 Standard plate count data for Run No. U3 133

70 Total coliform data for Run No. U3 134

71 Fecal coliform data for Run No. U3 135

72 Extreme-value frequency distribution of standard plate count data for Run No. U3 136

73 Extreme-value frequency distribution of total coliform data for Run No. U3 137

FIGURES (continued)

Number Page

74 Extreme-value frequency distribution of fecal coliform data for Run No. U3 138

75 Pilot Plant configuration for Run No. U4, March 6 & 7, 1975 139

76 Extreme-value frequency distribution of standard plate count data for Run No. U4 143

77 Extreme-value frequency distribtuion of total coliform data for Run No. U4 .144

78 Extreme-value frequency distribution of fecal coliform data for Run No. U4 .145

79 Pilot Plant configuration for Run No. U5, March 8 to July 14, 1975 146

80 Standard plate count data for Run No. U5 150

81 Total coliform data for Run No. U5 151

82 Fecal coliform data for Run No. U5 152

83 UV intensity versus log reduction of total coliforms for Run No. U5 153

84 UV intensity versus log reduction of fecal coliforms for Run No. U5 154

85 Extreme-value frequency distribution of standard plate count for Run No. U5 155

86 Extreme-value frequency distribution of total coliform data for Run No. U5 .156

87 Extreme-value frequency distribution of fecal coliform data for Run No. U5 .157

88 Pilot Plant configuration for Run No. U6, July 15 to August 3, 1975. 159

89 Standard plate count data for Run No. U6 162

90 Total coliform data for Run No. U6 163

91 Fecal coliform data for Run No. U6 164

FIGURES (continued)

Number Page

92 UV intensity versus log reduction of total coliform data for Run No. U6 165

93 UV intensity versus log reduction of fecal coliform data for Run No. U6 166

94 Extreme-value frequency distribution of standard plate count for Run No. U6 168

95 Extreme-value frequency distribution of total coliform data for Run No. U6 169

96 Extreme-value frequency distribution of fecal coliform data for Run No. U6 170

97 Pilot Plant configuration for Run No. U7; August 8 to October 5, 1975 171

98 Standard plate count data for Run No. U7 175

99 Total coliform data for Run No. U7 176

100 Fecal coliform data for Run No. U7 177

101 Extreme-value frequency distribution of standard plate count data for Run No. U7. 178

102 Extreme-value frequency distribution of total coliform data for Run No. U7 179

103 Extreme-value frequency distribution of fecal coliform data for Run No. U7 180

104 Pilot Plant configuration for Run No. U8; October 7 to November 31, 1975 181

105 Standard plate count data for Run No. U8 185

106 Total coliform data for Run No. U8 186

107 Fecal coliform data for Run No. U8 187

108 Extreme-value frequency distribution of standard plate count data for Run No. U8 188

109 Extreme-value frequency distribution of total coliform data for Run No. U8. 189

FIGURES (continued)

Number Page

110 Extreme-value frequency distribution of fecal coliform data for Run No. U8 190

111 Location of sampling stations, UV Virus Runs. 192

112 Meter readings with tap water from cold start 203

113 Meter readings after five minutes of purging with tap water 204

114 Meter readings on activated sludge effluent 205

115 Total coliform log reduction as a function of the calculated dose 225

116 Fecal coliform log reduction as a function of the calculated dose 226

117 F2 bacteriophage log reduction as a function of the calculated dose 227

118 Poliovirus log reduction as a function of the calculated dose 228

119 Virus reduction versus detention time 229

120 The effect of turbidity on percent transmittance. 231

121 Correlation between percent transmittance and total suspended solids 232

122 Correlation between transmittance at 254 nm and COD 233

123 Correlation between transmittance at 254 nm and TOC 234

124 Correlations between ammonia-N and COD and TOC 236

125 Correlation between NH_3-N and percent transmittance at 254 nm 237

126 Correlation between organic nitrogen and percent transmittance at 254 nm 238

127 Effect of cleaning the quartz sleeves on UV dose 239

128 Effluent suspended solids versus effluent fecal coliforms .240

FIGURES (continued)

Number — Page

129 Turbidity versus fecal coliforms 241

130 UV intensity versus percent transmittance. 243

131 Observed UV intensities versus log reduction in total coliforms 244

132 Observed UV intensities versus log reductions in fecal coliforms 245

133 Effluent fecal coliforms as a function of UV dose 246

134 Relationships between observed log reductions in fecal coliforms and the calculated and indicated UV dose . . . 248

135 Relationships between observed log reductions in total coliforms and the calculated and observed UV dose . . . 249

136 Fecal coliform densities with an exceedence probability greater than or equal to 5 percent versus indicated dose 250

137 Process configuration for light-dark study: August 1-19, 1975 253

138 Time-series plots of fecal coliform data for the light-dark study 257

139 Fecal coliforms in open basin versus covered basin . . . 258

TABLES

Number		Page
1	Summary of existing water supply for year 2020	3
2	Influent metals concentration for fiscal year 1975 . . .	12
3	Characteristics of raw wastewater at the White Rock STP for the period of October 1, 1974 through September 30, 1975	13
4	Technical data for the No. 1 aeration basin	20
5	Technical data for the No. 1 final clarifier	22
6	Media specifications for the No. 1 mixed-media filter. .	24
7	Results of Run No. K1, August 6, 1974	51
8	Performance of No. 1 activated sludge system during Run No. K2	55
9	Effect of flow rate on reduction of total coliforms, fecal coliforms, and standard plate count by ultraviolet light (Special Study of Sept. 14, 1974) . . .	56
10	Results of Run No. K2	57
11	Summary of No. 1 activated sludge system performance during Run No. K3	67
12	Results of Run No. K3	68
13	Performance of No. 1 activated sludge system and No. 2 multimedia filter during Run No. K4	77
14	Results of Run No. K 4	78
15	Performance of the No. 1 activated sludge system during Run No. K5	87
16	Results of Run No. K 5	88

TABLES (continued)

Number		Page
17	Performance of the No. 1 activated sludge system during Run No. U1	111
18	Results of Run U1	112
19	Performance of activated sludge and tertiary settling basin during Run No. U2	121
20	Results of Run U2	122
21	Performance of the activated sludge system and multimedia filter during Run No. U3	131
22	Results of Run U3	132
23	Performance of the No. 1 activated sludge system and upflow clarifier during Run No. U4	141
24	Results of Run U4	142
25	Performance of the No. 1 activated sludge system during Run No. U5	147
26	Results of Run U5	149
27	Performance of the activated sludge system and multimedia filters during Run No. U6	160
28	Results of Run U6	161
29	Performance of the No. 1 activated sludge system and multimedia No. 1 filter during Run No. U7	172
30	Results of Run U7	173
31	Performance of the No. 1 activated sludge system during Run No. U8	182
32	Results of Run U8	183
33	Operating summary of the first UV virus run	194
34	Results of chemical analyses of grab samples averaged over all four flow rates in the first virus run	195
35	Summary of the bacteriological data from the first virus run	196

TABLES (continued)

Number | | Page
36 Steady-state titers of F2 bacteriophage controls in first virus run 197

37 Titers of F2 bacteriophage exposed to ultraviolet radiation at different flow rates in first virus run 198

38 Titers of poliovirus type I exposed to UV radiation at different flow rates in first virus run 200

39 Summary of results from first virus run 201

40 Summary of dose-related data for the first virus run . . .202

41 Operating summary of second UV virus run 207

42 Results of chemical analyses of grab samples averaged over all four flow rates in the second virus run 208

43 Summary of the bacteriological data from the second virus run 209

44 Steady-state titers of F2 bacteriophage controls in first virus run 210

45 Titers of F2 bacteriophage exposed to ultraviolet radiation at different flow rates in second virus run 211

46 Titers of poliovirus type I exposed to UV radiation at different flow rates in second virus run 212

47 Summary of results from second virus run 214

48 Summary of dose related data for the second virus run . . .215

49 Summary of operations of virus run no. 3 216

50 Results of chemical analyses of grab samples averaged over all four flow rates in the third virus run 217

51 Summary of the bacteriological data from the third virus run 219

52 Steady-state titers of F2 bacteriophage controls in third virus run 220

53 Titers of F2 bacteriophage exposed to ultraviolet radiation at different flow rates in third virus run 221

TABLES (continued)

Number Page

54 Titers of poliovirus type I exposed to UV radiation at different flow rates in third virus run 222

55 Summary of results from third virus run 223

56 Summary of dose-related data for the third virus run . . .224

57 Summary of the data for the Kelly-Purdy disinfection unit 251

58 Summary of the data for the UPS disinfection unit 251

59 Process control and operation summary light-dark study: August 1-19, 1975 .254

60 Chemical and bacteriological summary of the light-dark study, August 1-19, 1975 255

61 Analysis of mean coliform densities in light-dark study . .259

ACKNOWLEDGEMENT

This report is the product of cooperative effort by so many people that individual mention becomes unfeasible. To the entire group of Dallas Water Utilities personnel and the Texas A&M Research Foundation members we want to convey our gratitude for their support and cooperation.

In particular we want to offer our thanks to Mr. Henry J. Graeser, Director, Dallas Water Utilities, who originated the plan and inspired the effort; and Dr. I.M. Rice, Assistant Director for Engineering and Planning during the program and presently the successor to Mr. Graeser as Director, for grant preparation and financial planning in addition to general grant administration.

We gratefully acknowledge the cooperation offered by Dr. Gerald Berg and his staff from the Environmental Protection Agency, Cincinnati, Ohio, including especially Dr. Robert Safferman and Mr. Donald Berman for designing and helping conduct the poliovirus experiments.

SECTION 1

INTRODUCTION

As shown in Figure 1, the City of Dallas in North Central Texas is situated in the upper Trinity River Watershed. This region must be classified as naturally water deficient; in fact, there is only one natural lake in the whole of the State of Texas. In the upper Trinity River Basin, average annual precipitation ranges from about 100 centimeters per year in the eastern portions to 50 centimeters per year in the westerly sections. In general, average annual precipitation and evaporation rates are about equal, and drought periods in excess of 60 days are not uncommon. These factors combine to make water a very valuable resource in North Central Texas.

The City of Dallas derives its drinking water supply from the extensive reservoir network shown in Figure 1, and estimates indicate that an adequate supply of fresh water exists to meet demands anticipated to the year 1995. The water supply is derived from six reservoirs on three watersheds, with estimated safe yields for the year 2020 in Table 1.

During the middle 1950's North Central Texas experienced a protracted drought. The City of Dallas investigated two alternate sources of water to augment its dwindling supply. One was to pump water from the highly mineralized Red River into the existing reservoir system, and the other was to utilize the waters of the West Fork of the Trinity River which carry a considerable amount of pollution from the wastewater effluents of the City of Ft. Worth and of the mid-cities between Ft. Worth and Dallas. In 1955 the thought of "drinking someone else's sewage" did not meet with wide acceptance from either the general public or the City Council and the decision was made to import water from the Red River. Consequently, the City survived the drought by utilizing the Red River over a three-year period -- but not without effect (1). A most important point emerging from this period is that as early as 1955 a major American city had seriously evaluated the possiblity of an indirect wastewater reuse as an alternate supply of drinking water.

With respect to total water resources management in the upper Trinity River Basin, indirect but intentional wastewater reuse is of considerable importance to the City of Dallas. Both the Bachman and the Elm Fork Water Purification Plants of the City of Dallas withdraw water from the Elm Fork of the Trinity River. Estimated water supply for the year 2020 includes 329,000 cu m per day (86.8 MGD) from Garza-Little Elm Reservoir, 38,000 cu m

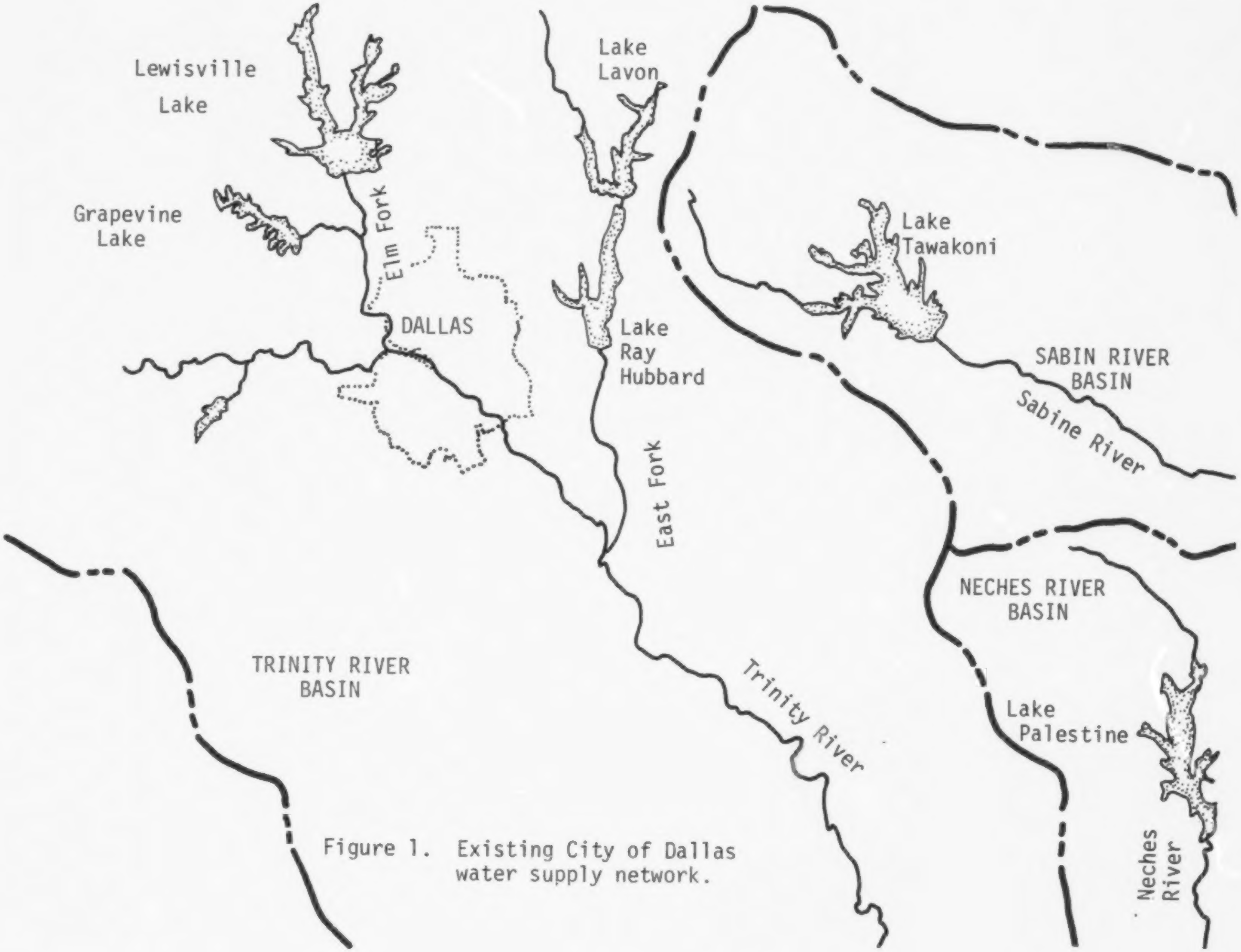

Lewisville
Lake
Grapevine
Lake
Elm Fork
DALLAS
Lake
Lavon
Lake
Ray
Hubbard
East Fork
Lake
Tawakoni
SABIN RIVER
BASIN
Sabine River
NECHES RIVER
BASIN
Lake
Palestine
Neches
River
TRINITY RIVER
BASIN
Trinity River

Figure 1. Existing City of Dallas water supply network.

TABLE 1. SUMMARY OF EXISTING WATER SUPPLY FOR YEAR 2020

Reservoir and Basin	Estimated Safe Yield MGD	M^3/day
Trinity River Basin		
Lewisville (Garza-Little Elm)	86.8	329,000
Grapevine	10.0	38,000
Ray Hubbard	55.4	210,000
Lavon	10.0	38,000
Return flows	41.3	156,000
Sabine River Basin		
Tawakoni	163	616,000
Neches River Basin		
Palestine	102	386,000
TOTAL AVAILABLE SUPPLY	468	1,773,000

per day (10.0 MGD) from Grapevine Reservoir, and 156,000 cu m per day (41.3 MGD) in return flows. The return flows are composed exclusively of wastewater effluents discharged approximately 33 kilometers (20 miles) upstream from the water treatment plant intake structures. The return flows constitute 30 percent of the 523,000 cu m per day (138 MGD) that will be used as a source of drinking water, and represent a valuable water resource. However, travel time from the point of discharge to the most distant intake structure is less than one day, allowing little time for significant natural purification to occur. Under these circumstances, the City of Dallas has considerable interest in water and wastewater treatment technology since it is imperative that the public health be safeguarded.

Bearing in mind the occasional shortages of rainfall and the consequences of a prolonged drought, and knowing also that new sources of supply are disappearing rapidly, the City of Dallas has felt for some years that the building of new reservoirs on streams to augment the potable water supply would become virtually impossible. The fact that eastern cities in particular have been able to produce potable, palatable waters from rivers that have been increasingly polluted has led to consideration that some day the recycle of wastewaters, properly treated, may actually be a means of survival in the semiarid Southwest and West.

Dallas has for several years pursued studies of wastewater and water treatment methods that might lead to the production of potable water completely acceptable for all uses. Because there are technological, legal, and esthetic considerations to be satisfied, Dallas has followed a cautious policy that more than is known now must be learned about constituents of wastewater proposed for reuse. The three large areas still relatively unsatisfied are viruses, heavy metal, and organics. Any or all of these may be found to some degree in recycled waters, and enough work must be done to satisfy all parties that no significant risk attaches to either health or comfort from the prolonged use of such waters. Dallas will want to know that the most stringent standards can be met before proposing recycle.

BACKGROUND OF THE DALLAS PROGRAM

As a result of the previously described circumstances, namely, the consideration of using the heavily polluted West Fork of the Trinity in 1955, the present indirect use of upstream effluents, however minor, and the economics dictating that maximal amounts of wastewaters be salvaged if practical, the Dallas Water Utilities have pursued an active, viable wastewater reuse research program since June 1970.

The Demonstration Plant of the Dallas Water Reclamation Research Center, which is described in detail in a subsequent section of this report, was built and brought on-line in late July 1969. Equipment check-out and/or modification consumed at least nine months, and the facility was in service for almost a year before the staff considered it to be truly operational. Additionally, a laboratory and administration building was constructed to provide laboratory capabilities for the research program and office space for several different Water Utilities Department activities. The laboratory facilities were occupied in the Spring of 1971.

The funds for construction of the laboratory and administration building were provided by Federal Grant No. WPC Tex 588, to the amount of $571,093 of which the City provided 52 percent. The Demonstration Plant was constructed under Grant No. 17080 EKG from the Environmental Protection Agency (EPA) for a total cost of $689,015 of which the City of Dallas provided 45 percent.

From start-up until January 1971, the Dallas Water Reclamation Research Center operated on additional funds provided in Grant No. 17080 EKG for the study of various water reclamation unit processes. The initial phase of the project was directed at evaluating different sequences of unit processes to expand and up-grade the City's Central Wastewater Treatment Plant.

At the conclusion of these studies additional unit processes were investigated by utilizing a number of different wastewaters as influents to the unit processes at the Demonstration Plant. For the most part the investigations were short term (2 to 4 weeks), and these data have been presented in the Final Report for the project (2).

From June 1972 through February 1974 the Research Center evaluated the removal of metals and viruses through three different advanced wastewater treatment sequences. Concentrations for over twenty different metals were evaluated in the influent and effluent of each unit process over the protracted study period. This project was funded through Grant No. S-801026 from EPA for a total cost of $200,287, of which the City shared 41 percent (3, 4).

RESEARCH PRESENTED IN THIS REPORT

The present project, Grant No.R-803292, was started in June 1974 and concluded during November 1975. This project was conducted in two phases, both of which had distinctly different research objectives.

Characterization for Potable Reuse

In the first part of this research effort the selected treatment train was operated to produce the best possible quality of effluent. This product water was then examined in the light of present and proposed standards for its potential reuse as a potable water. The objectives were:

1. Production of a high-quality product water.
2. Monitoring of the effluent for parameters to indicate whether potable quality according to available criteria had been achieved.
3. Evaluating the reliability of the sequence of unit processes utilized in the study as it related to wastewater reuse.

Ultraviolet Disinfection of Municipal Effluents

Phase two of this project was a study of the feasibility of utilizing ultraviolet light as a disinfection process for municipal wastewater effluents. The objectives of the ultraviolet disinfection project were as follows:

1. Evaluate the feasibility of using ultraviolet light as a disinfection process for municipal wastewater effluents.
2. Determine whether any additional treatment is required to achieve a consistent fecal coliform density less than 200 per 100 mls.
3. Evaluate the effect of photo-reactivation.

This research effort was conducted for a total cost of $262,754 of which the EPA provided 27 percent of the funds and the City of Dallas the remainder.

Since the two portions of the study had such different objectives, this report discusses only the research effort conducted during the second phase of the project. The work performed during the first phase of the reuse portion of the project has already been reported (5).

SECTION 2

CONCLUSIONS

This research effort leads to several conclusions that bear upon disinfection technology.

This effort was principally a feasibility study to evaluate ultraviolet light irradiation as an alternate disinfection technique for secondary effluents. The conclusion of all personnel associated with the project is that UV light does present a viable disinfection process for secondary effluents. This research indicates that an activated sludge effluent can be adequately disinfected with UV light to comply with the 200 fecal coliforms per 100 mls disinfection criterion.

Shallow tray exposure chambers similar to the Kelly-Purdy system used in this research should not be used for secondary effluents. Solids deposition in the bottom of the exposure chamber constituted a problem of major proportions, and no economical solution to this problem is apparent at this time. Additionally, large surface areas are required. For instance, a flow of 43.8 liters per second (1 MGD) would require an exposure chamber with a surface area of approximately 58 sq. meters (625 sq.ft.). Finally, the shallow-tray chambers are not capable of taking advantage of light emmission from the full 360 degrees around the lamps. This single factor results in the shallow-tray design being less energy efficient than the exposure chambers which utilize submerged lamps.

Total suspended solids within the range 5 to 50 mg/l had very little or no effect on the ability of the water to transmit UV light. The effect of TSS on UV light transmission outside of this range was not investigated.

The studies conducted with attenuated Type I Poliovirus indicate that ultraviolet light disinfection can also be effective against animal viruses. The data indicate that the virus kill obtained is a function of the UV dose used, and the correlation is excellent.

Virus inactivation studies conducted with an F2 coliphage, and in conjunction with the poliovirus research, indicates that the coliphages are good indicators of animal virus response to UV disinfection processes.

Light transmission measured at 254 nm with an ultraviolet spectrophotometer provides data which are absolutely essential to determination of UV dose. Additionally, of the two principal factors affecting the actual UV dose, UV transmissibility and flow, flow is the least significant. Several efforts were made to quantify the effect of flow on observed kill, and the results were generally disappointing. For hydraulic transients to be of much real significance the actual residence time must be changed by about one log, and in practice this is very unlikely to occur.

The turbidity of the effluents being disinfected did not affect the ability of the liquid to transmit UV light. This conclusion is valid within the range of turbidity values encountered during this research effort (0.5 to 12 NTU), and no effort was made to validate this conclusion at higher turbidity values.

Ultraviolet light disinfection systems employing submerged lamps represent the preferred exposure chamber configuration. These systems are capable of utilizing all radiation emitted by the lamps, and are therefore, more energy efficient than the shallow-tray design.

Over the ranges of the many variables encountered in the project, UV dose was the one factor that had the most pronounced effect on the observed kill and the number of organisms found in the effluent. In order to achieve adequate kills on a typical secondary effluent, the UV dose necessary appears to be in the range of 30,000 to 35,000 microwatt-seconds per square centimeter. As used in this report, dose is the average UV light intensity in the water being disinfected multiplied by the theoretical residence time of the exposure chamber used.

The monitoring of UV intensity at some point in the exposure chamber is absolutely essential for process control. This measurement can be made easily and routinely and is directly related to the UV dose the effluent is receiving.

The development of slime around the UV lamps must be controlled to prevent a decrease in UV dose. Routine UV intensity measurements can be used to determine when the unit must be cleaned. This did not represent a major problem during the project, and a cleaning interval of about two weeks seems reasonable, although the cleaning frequency will be dependent on water quality to a certain degree and perhaps temperature.

As with any other disinfection process, the efficiency of UV light is a function of the quality of the water to be disinfected. This research had demonstrated conclusively that UV light is more effective on a nitrified activated sludge effluent than on a non-nitrified effluent. The presence of ammonia nitrogen should have nothing to do with the UV kill mechanism, and one must conclude that the higher quality effluent produced as a direct result of nitrification has improved UV transmission characteristics, which results in a higher effective UV dose.

SECTION 3

RECOMMENDATIONS

Additional studies should be performed with larger systems to permit accurate estimation of the cost associated with the operation of UV disinfection systems. The manufacturer of the lamps estimates the bulb life at 7000 hours (about 10 months), but the UV output decreases as lamp operating time increases, and the effective life is unknown. The effect on dose of using different materials of construction is also not known to the authors. Also, the actual amount of operator time required by these systems can only be determined more accurately by large scale operation over determined extended periods of time, since seasonal effects on water quality may be a factor.

The UV dose data in this report have been presented in units of energy per unit area (μwatt-sec/cm^2). In an enclosed chamber such as the UPS unit, there is no plane surface upon which the UV energy impinges. With this type of geometry it is not possible to directly measure the average UV intensity in the water being irradiated, and it is equally impossible to make an accurate dose calculation. A very real need exists to develop a reliable procedure for directly measuring UV dose that is relatively simple and rapid.

Nitrified operation of a biological wastewater treatment facility has again been shown to produce a "superior" effluent -- in this case, an increased transmissibility for UV light. The longer sludge ages associated with nitrified operation apparently result in a more diverse biological population which, in turn, breaks down more of the organic materials, rendering the medium more transmissible to UV. Certainly more information should be learned about these phenomena, so that greater use can be made of the many advantages they offer in an environmental context.

SECTION 4

DESCRIPTION OF RESEARCH FACILITIES

CITY OF DALLAS COLLECTION SYSTEM

The sanitary sewer collection system serving the City of Dallas consists of 5074 kilometers (3,137 mi) of gravity mains. During the fiscal year covered in this report the City abandoned 2.54 kilometers (1.58 mi) of sanitary sewer main, and added 35.1 kilometers (21.8 mi) of mains to the collection system. The best available estimates indicate that the total length of laterals is between one and two times the length of the gravity mains, indicating a total collection system length between 10,000 and 15,000 kilometers (6215 and 9323 miles). The City has no combined sewers.

In addition to the normal domestic wastes discharged to the collection system, the City has significant contributions from industrial and commercial establishments. During fiscal year 1974 the industrial discharges represented 12.1 percent of the total flow received at the Central Plant, or 21.9×10^6 cu m (5.80×10^9 gal) per year. The 221 significant industries monitored by the Water Utilities Department discharged a total of 1.70×10^7 kg of BOD_5 (3.74×10^7 lbs) and 1.38×10^7 kg (3.03×10^7) of total suspended solids(TSS) to the collection system during fiscal year 1974. When expressed in terms of concentration, the BOD_5 and TSS of the industrial discharges were 773 mg/l and 626 mg/l, respectively. The BOD_5 discharge represented 37.7 percent of the total load entering the Central Plant, while the industrial TSS discharges represented 30.7 percent of the total TSS load.

The activities of commercial establishments, which include restaurants, wholesale food preparation facilities, and service facilities (principally car washes) substantially impact on wastewater characteristics. The predominant effect of commercial activities that one would normally expect would be to increase the organic and solids loadings; however, certain of the service activities (car washing) can have appreciable impact on metals concentrations.

The concentrations of certain metals in the influents of the Dallas and White Rock plants are given in Table 2. The column headed "combined" is a calculated, flow-weighted concentration for all wastewaters arriving at the Central Plant. Typical data for the raw wastewater entering the White Rock STP are presented in Table 3, and upon inspection,the waste-

TABLE 2. INFLUENT METALS CONCENTRATIONS FOR FISCAL YEAR 1975

Metal	Concentration (mg/l)		
	Dallas STP	White Rock STP	Combined
Arsenic	0.005	0.020	0.016
Barium	0.7	0.7	0.7
Boron	0.51	0.39	0.42
Cadmium	0.035	0.016	0.020
Chromium	0.34	0.11	0.17
Copper	0.23	0.14	0.16
Lead	0.44	0.19	0.25
Manganese	0.10	0.08	0.08
Mercury	0.0016	0.0012	0.0013
Nickel	0.21	0.09	0.12
Selenium	-----	-----	-----
Silver	0.017	0.016	0.016
Zinc	0.580	0.227	0.311

TABLE 3. CHARACTERISTICS OF RAW WASTEWATER AT THE WHITE ROCK STP FOR THE PERIOD OF OCTOBER 1, 1974 THROUGH SEPTEMBER 30, 1975*

		n
Flow	409,000 cu.m./day (108.0 mgd)	365
Grit	0.0127 liters/cu.m. (1.69 cu.ft./10^6 gal)	300
Total Solids	844 mg/l	350
Settleable Solids	8.4 ml/l	350
Total Suspended Solids	209 mg/l	350
COD	417 mg/l	350
BOD_5	191 mg/l	350
NH_3-N	16.4 mg/l	350
Org. N	13.5 mg/l	350
NO_2 & NO_3-N	0.3 mg/l	350
pH	7.2	350

*Arithmetic means of 24-hour flow-weighted, composite samples collected daily.

water appears to be representative of domestic wastewaters. Most of the industrial waste discharges enter the Dallas STP, and for this reason the wastewaters entering the White Rock plant are more suitable for wastewater reuse studies.

TREATMENT FACILITIES

The demonstration plant of the Dallas Water Reclamation Research Center is colocated with the White Rock Sewage Treatment Plant (STP) at the City of Dallas' Central Wastewater Treatment Facility. The Central Plant complex is situated on the south bank of the Trinity River approximately five kilometers (3 miles) south of the City's central business district. The Central Plant actually consists of the three treatment facilities described below, two of which are trickling filter plants. The third facility is completely-mixed activated sludge followed by tertiary mixed-media filtration.

Dallas Sewage Treatment Plant

The Dallas STP is the oldest wastewater treatment facility operated by the City of Dallas. This single-stage, standard-rate, trickling filter facility consists of four bar screens and grit channels, twenty-four Imhoff tanks which are operated as primary clarifiers, two rectangular primary clarifiers, sixteen standard-rate trickling filters which are 53 meters (174 feet) in diameter, and three final clarifiers.

White Rock Sewage Treatment Plant

The White Rock STP is a two-stage, high-rate trickling filter facility without intermediate clarification. The plant consists of two bar screens and grit channels, six rectangular primary clarifiers, four first-stage, high-rate trickling filters, eight second-stage, high-rate trickling filters, and four rectangular final clarifiers. All trickling filters are 53 meters (174 feet) in diameter, and contain a maximum of 2.3 meters (7.5 feet) of media.

Tertiary Treatment Complex

Under normal flow conditions the effluents from both the Dallas and White Rock facilities are discharged to the tertiary treatment complex prior to discharge into the Trinity River. The tertiary complex consists of twelve completely-mixed, activated sludge aeration basins and twelve final clarifiers, followed by fourteen mixed-media gravity filters. The physical relationship between the individual facilities, present at the Central Plant complex can be seen in Plate 1.

Demonstration Plant

All influents to the demonstration plant are pumped from the White Rock STP and all effluents and sludges from the pilot plant are returned to

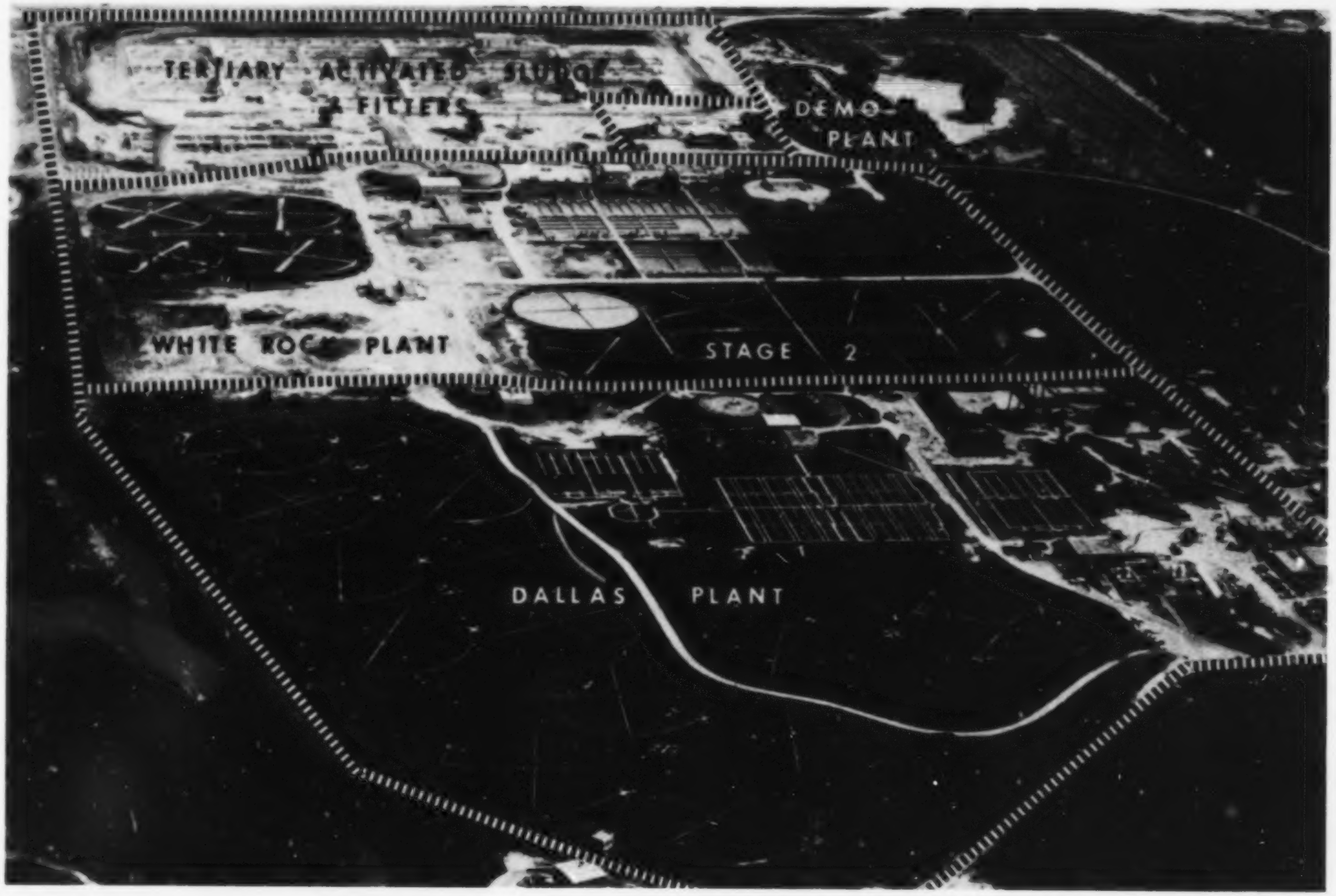

TERTIARY ACTIVATED SLUDGE
& FILTERS
DEMO PLANT
WHITE ROCK PLANT
STAGE 2
DALLAS PLANT

Plate 1. Overall view of the Central Wastewater Treatment Facility looking south.

the headworks of the White Rock plant. As indicated in Figure 2, there are a total of five possible influents which can be supplied at a maximum flow of 47.3 liters/sec (750 gpm), with the exception of the raw sewage pump that is rated at 18.9 liters/sec(300 gpm). The discharges from all pumps are routed to a valve station at the White Rock plant, from which the flow is directed to the pilot plant through one of three main influent lines. Each influent line services one of the major treatment modules (biological, chemical, or physical) at the demonstration plant.

As indicated in Figure 3, which is a piping diagram of the major components of the demonstration plant, the facility is relatively complex and very flexible. The following unit processes are present at the pilot plant, and many are identified in Plate 2 (aerial photograph of the demonstration plant).

1. No. 1 completely-mixed activated sludge system.
2. No. 2 completely-mixed activated sludge system.
3. Upflow clarifier.
4. Gravity-flow, mixed-media filter.
5. Gravity-flow, dual-media filter.
6. Gravity-flow activated carbon contactors (2 each).
7. Chlorine contact basins (2 each).
8. Ozone generator and contacting system.
9. Reverse osmosis deminerialization unit.
10. Ultraviolet light disinfection units (2 each).
11. Chemical storage and feeding equipment.

No. 1 Activated Sludge System---

The No. 1 activated sludge system consists of the No.1 aeration basin and the No. 1 final clarifier, and return sludge and effluent pumps. The return sludge pump has a practical operating range of 6.3 to 47.3 liters/sec. (100 to 750 gpm), while the effluent pump has an operational range of 3.2 to 20.5 liters/sec. (50 to 325 gpm).

No. 1 Aeration Basin--

The No. 1 aeration basin is a circular mild-steel tank, erected above ground; technical data for this unit are summarized in Table 4. Several different types of mixing and oxygen transfer equipment have been evaluated in this basin. The original equipment was supplied by Dorr-Oliver, which consisted of an 18.6 kw (25 HP) surface/submersed turbine variable-speed mixer and an 11.2 kw (15 HP) variable-speed air compressor.

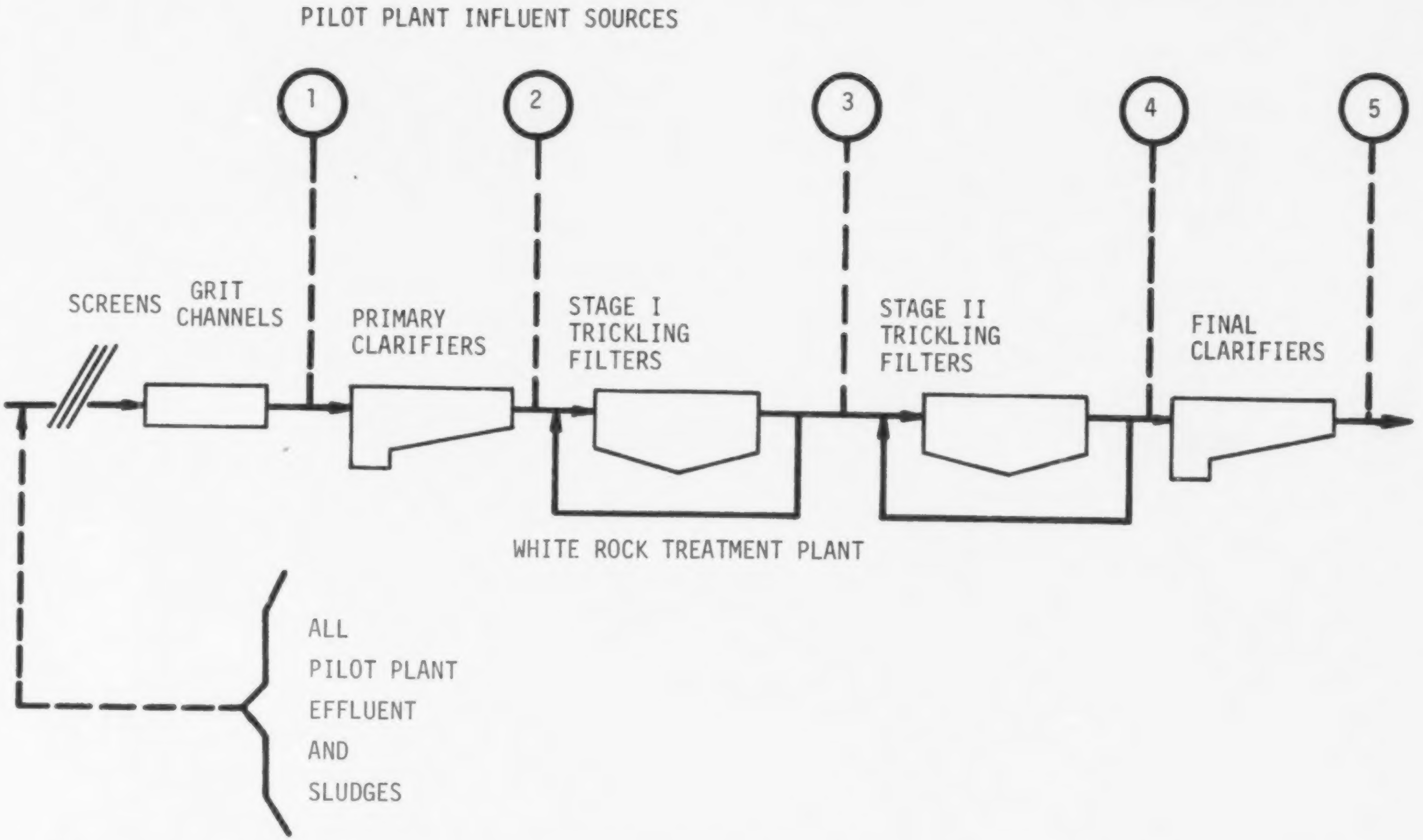

PILOT PLANT INFLUENT SOURCES
1
2
3
4
5
SCREENS
GRIT CHANNELS
PRIMARY CLARIFIERS
STAGE I TRICKLING FILTERS
STAGE II TRICKLING FILTERS
FINAL CLARIFIERS
WHITE ROCK TREATMENT PLANT
ALL PILOT PLANT EFFLUENT AND SLUDGES

Figure 2. Possible Sources of Influents for the Pilot Plant at the White Rock Sewage Treatment Plant.

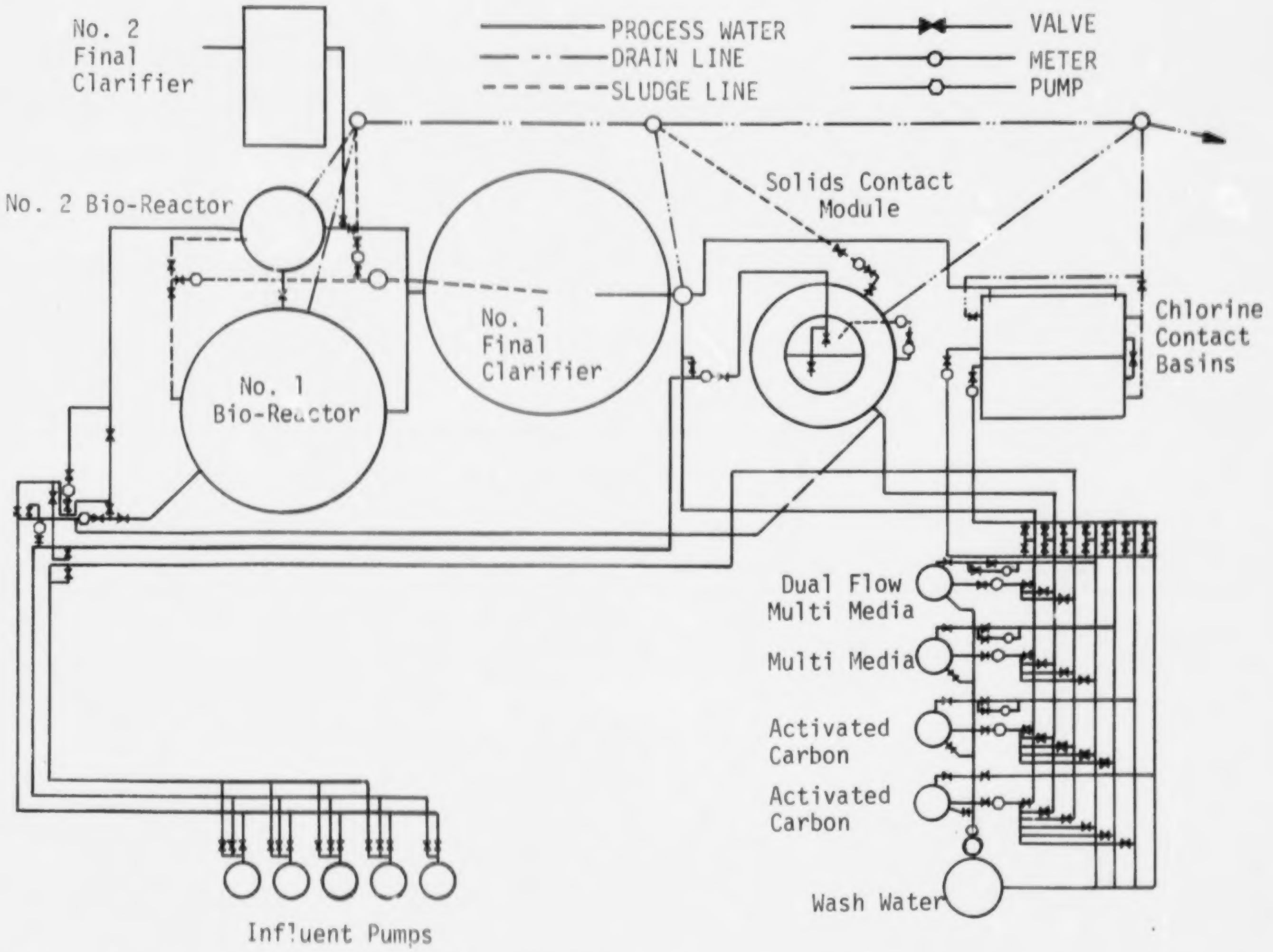

No. 2
Final
Clarifier
PROCESS WATER
DRAIN LINE
SLUDGE LINE
VALVE
METER
PUMP
No. 2 Bio-Reactor
Solids Contact
Module
No. 1
Final
Clarifier
No. 1
Bio-Reactor
Chlorine
Contact
Basins
Dual Flow
Multi Media
Multi Media
Activated
Carbon
Activated
Carbon
Wash Water
Influent Pumps

Figure 3. Flow Schematic of the Dallas Water Reclamation Research Center Demonstration Plant

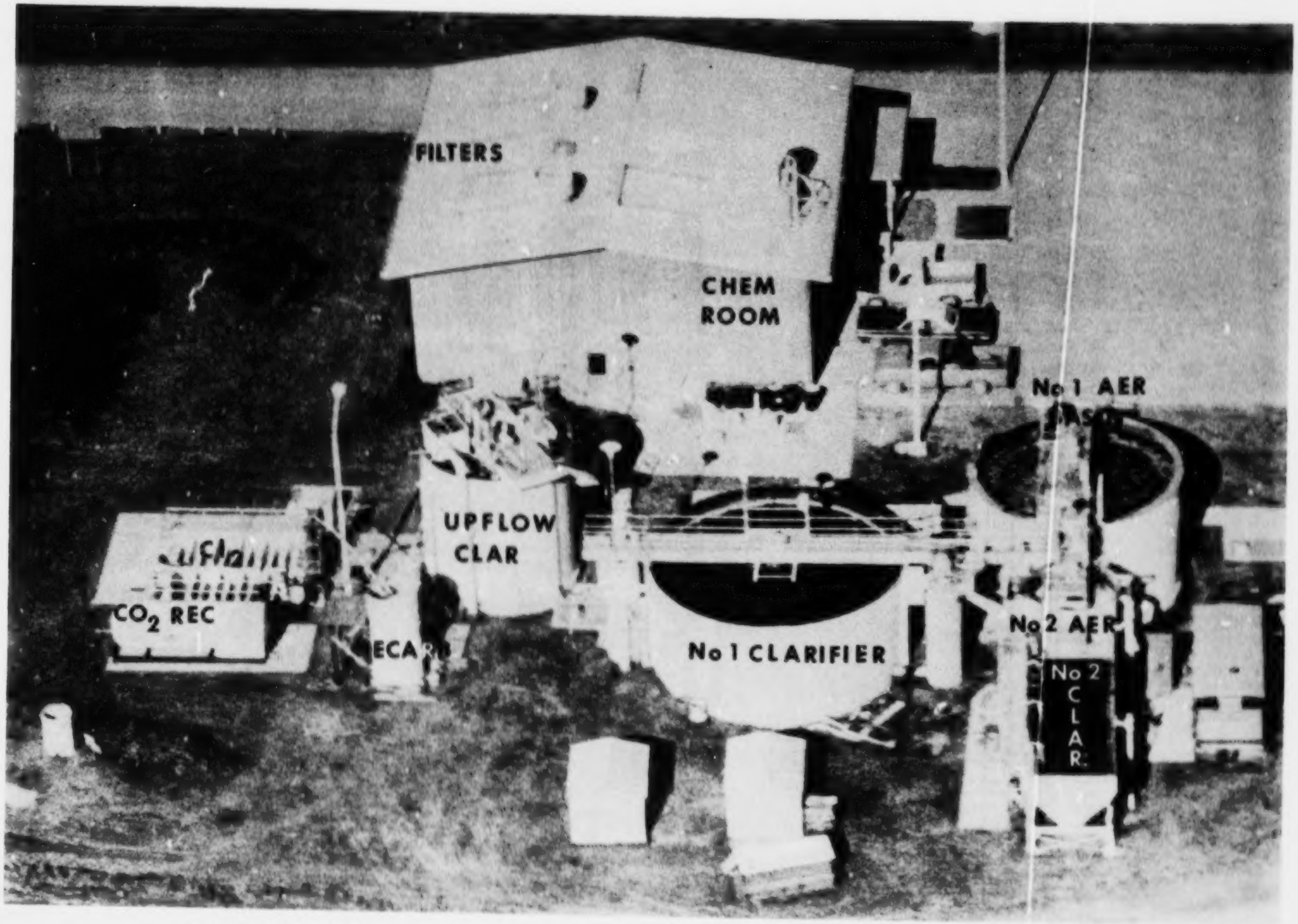

FILTERS
CHEM ROOM
No 1 AER
UPFLOW CLAR
No 1 CLARIFIER
No 2 AER
No 2 CLAR
CO_2 REC
ECA

Plate 2. Aerial photograph of the Demonstration Plant.

TABLE 4. TECHNICAL DATA FOR THE NO. 1 AERATION BASIN

Diameter	7.62 m (25.0 ft.)
Depth	3.66 m (12.0 ft.)
Volume	560 m^3 (45,000 gal)
Theoretical Residence Time at 6.3 liters/sec (100 gpm)	7.5 hours
Total Nameplate Power Input	29.8 kw (40 HP)
Maximum Power Level	0.053 kw/m^3 (0.89 HP per 1000 gal)
Air Flow	118 or 235 liters/sec* (250 or 500 scfm)*

*Depending upon number of compressors used.

This system was removed and replaced with Fiscalin equipment. Aquarius, Inc. is the manufacturer of the Fiscalin system, which was operated throughout most of the reuse portion of this grant. During the UV phase of this research effort the Aquarius equipment was replaced by a "jet aeration" system manufactured by Pentech/Houdaille.

No. 1 Final Clarifier---

The No. 1 clarifier is a circular, mild-steel basin erected above ground. As initially provided by Rex Chainbelt the unit had peripherial feed and square effluent weirs in the center of the tank. The unit was not originally equipped with a surface skimmer, and the center effluent weir configuration made addition of a skimmer quite complex. Therefore, the basin was modified by removing the center effluent weirs and bolting a new peripherial effluent weir to the inside of the existing influent baffle skirt. A skimmer and scum collector were then fitted to the basin.

Sludge is removed by the head differential between the water surface in the clarifier and the return sludge pump well, via a single armed header. Technical data for this clarifier are presented in Table 5.

No. 2 Activated Sludge System---

The No. 2 activated sludge system consists of the 28.4 m^3 (7500 gal) completely-mixed aeration basin, and a three-hopper Smith and Lovelace final clarifier. The aeration basin has a diameter of 3.14 m (10.3 ft.) and a side water depth of 3.66 m (12.0 ft.). Mixing and oxygen transfer is affected by diffusers, and the maximum air flow is 53.8 liters/sec. (114 scfm).

Upflow Clarifier---

An Infilco Densator is the chemical treatment unit used at the demonstration plant. The unit consists of the main tank, 5.5 m in diameter and 5.5 m deep, and an inner cylinder that serves as the rapid mixing and flocculation zones. Influent enters the top of the inner cylinder and the main tank serves as the upflow clarification compartment.

Energy input for mixing and flocculation is supplied via independent turbine-type mixers, each of which is equipped with a U.S. Electric Varidrive that has a 10 to 1 turndown capability.

A 2.54 cm x 10.2 cm (1 in. x 4 in.) steel fluidizer bar is used to prevent the sludge from over compacting.

Chemical Storage and Feed Equipment---

Facilities are present at the demonstration plant to store and feed the following chemicals:

1. Hydrated lime

2. Hydrated aluminium sulfate

TABLE 5. TECHNICAL DATA FOR THE NO. 1 FINAL CLARIFIER

Diameter	9.14 m (30.0 feet)
Depth	3.66 m (12.0 feet)
Volume	240 m^3 (63,500 gal.)
Surface Area	65.7 m^2 (707 $feet^2$)
Weir Length	27.1 m (89 feet)
Surface Overflow Rate at 6.3 liters/sec (100 gpm	8.50 m^3/m^2/day (2.4 gpd/$ft.^2$)
Weir Loading at 6.3 liters/sec (100 gpm)	20.1 m^3/m/day (1620 gpd/$ft.^2$)

3. Ferric chloride

4. Dry polyelectrolytes

5. Liquid polyelectrolytes

6. Activated silica

7. Powdered activated carbon

8. Chlorine

All coagulants and coagulant aids, with the exception of lime, can be fed to either aeration basin or final clarifier, to the upflow clarifier, or in front of the filters or carbon contactors for use as filtration aids. The lime slurry can be pumped to either of the activated sludge systems or the upflow clarifier.

No. 1 Mixed-Media Filter--

The No. 1 filter initially consisted of 0.91 meters (3.0 feet) of sand overlayed with 0.30 meters (12 inches) of anthracite. The influent flow was split equally between the top and bottom of the filter bed, and the effluent was withdrawn through a mid-bed collector located 15 cm (6 inches) below the sand-anthracite interface. The filter performance can be characterized as having been generally good; however, structural deficiencies with the mid-bed collector resulted in frequent maintenance and the unit was converted to a conventional gravity-flow filter.

When the filter was rebuilt media supplied by Neptune Microfloc was utilized and the media specifications are summarized in Table 6. The filter has a nominal diameter of 1.21 meters (4.0 feet) and a surface area of 1.17 sq.m. (12.6 sq.ft.). At a flow of 2.37 liter/sec. (37.5 gpm) the filtration rate if 175 cu m per sq. m. per day (3 gpm/sq.ft.). Filter backwashing is conventional, and utilizes a surface wash in lieu of an air scrub.

No. 2 Dual-Media Filter--

Structually, the No. 2 filter is almost identical to the No. 1 filter, and this unit is also operated in the conventional gravity-flow mode. Media consist of 30.48 cm (12 inches) of sand with a 60.96 cm (24 inches) anthracite cap. The filter sand has an effective size of 0.57 mm and a uniformity coefficient of 1.6. Air scour is normally used prior to backwash at a rate of 20.2 liters per sec per sq m (4 scfm per sq ft).

Chlorine Contact Basins--

The demonstration plant has two chlorine contact basins which may be operated in parallel or in series. Each basin is 5.49 meters (18.0 feet) long, 2.26 meters (7.41 feet) wide, and 0.48 meters (1.58 feet) deep.

TABLE 6. MEDIA SPECIFICATIONS FOR THE NO. 1 MIXED-MEDIA FILTER

Material	Size	Depth	Effective Size	Uniformity Coefficient
Gravel	1.91 to 1.27 cm (3/4 to 1/2 in.)	7.62 cm (3 in.)		
	1.27 to 0.64 cm (1/2 to 1/4 in.)	7.62 cm (3 in.)		
	0.64 cm (1/4 in.)	5.08 cm (2 in.)		
Garnet				
Coarse, MS-11		7.62 cm (3 in.)	0.87 mm	1.17
Fine, MS-7		11.43 cm (4.5 in.)	0.27	1.22
Sand, MS-18		24.13 cm (9.5 in.)	0.41 mm	1.32
Anthracite, MS-19		55.88 cm (22 in.)	1.05 mm	1.35

Total Depth of Filter Media = 99.06 cm (39 inches)

Each basin has a volume of 5.95 cu.m. (1570 gal.), which results in a theoretical residence time of 15.7 minutes at a flow of 6.31 liters per sec. (100 gpm). Eleven fiberglass baffles were installed in each basin, such that plug flow would be closely approximated. Dye studies have been used to quantify the hydraulic characteristics of the end-around baffling system, and observed residence time distribution functions closely approximate theoretical values. The chlorination equipment is capable of a maximum feed of 22.7 kg (50 lbs.) of chlorine per day.

Ultraviolet Light Disinfection Units--

Kelly-Purdy UV Unit-- The Kelly-Purdy ultraviolet light disinfection unit consisted of a shallow-tray exposure chamber of 185 cm (6 feet) long, 92 cm (3 feet) wide, and 9.2 cm (3-5/8 inches) deep. Flow entered and exited the unit on the narrow ends of the unit as shown in Figure 4.

Thirteen 30-watt ultraviolet lamps (G30T8) were mounted above the exposure chamber. The influent flow was measured with an undulating disc meter, and water depth in the unit was controlled by changing the elevation of the effluent weir. A photograph of the unit is shown as Plate 3.

U.P.S. Model EP-50-- A model EP-50 ultraviolet light disinfection unit manufactured by Ultraviolet Purification Systems, Inc., of Scarsdale, New York was used during this study. The unit consisted of a 53.6 liter (14.2 gallons) stainless steel cylindrical chamber that housed nine longitudinally-mounted 40-watt UV lamps. Each lamp was enclosed by a quartz sleeve and had an individual ammeter on the control panel. The effective arc length of the lamps was 76 cm. The UPS unit is shown in Plate 4.

The UPS unit, as shipped from the factory, was equipped with a water quality meter. This meter measured gross ultraviolet light intensity on a unitless scale. Through the course of the investigations, the water quality meter proved unreliable and was used only as a general indicator of UV intensity.

All UV intensity measurements during the course of the project were made with an IL 500 radiometer manufactured by International Light, Inc., a division of Dexter Industrial Green, Newburyport, Massachusetts.

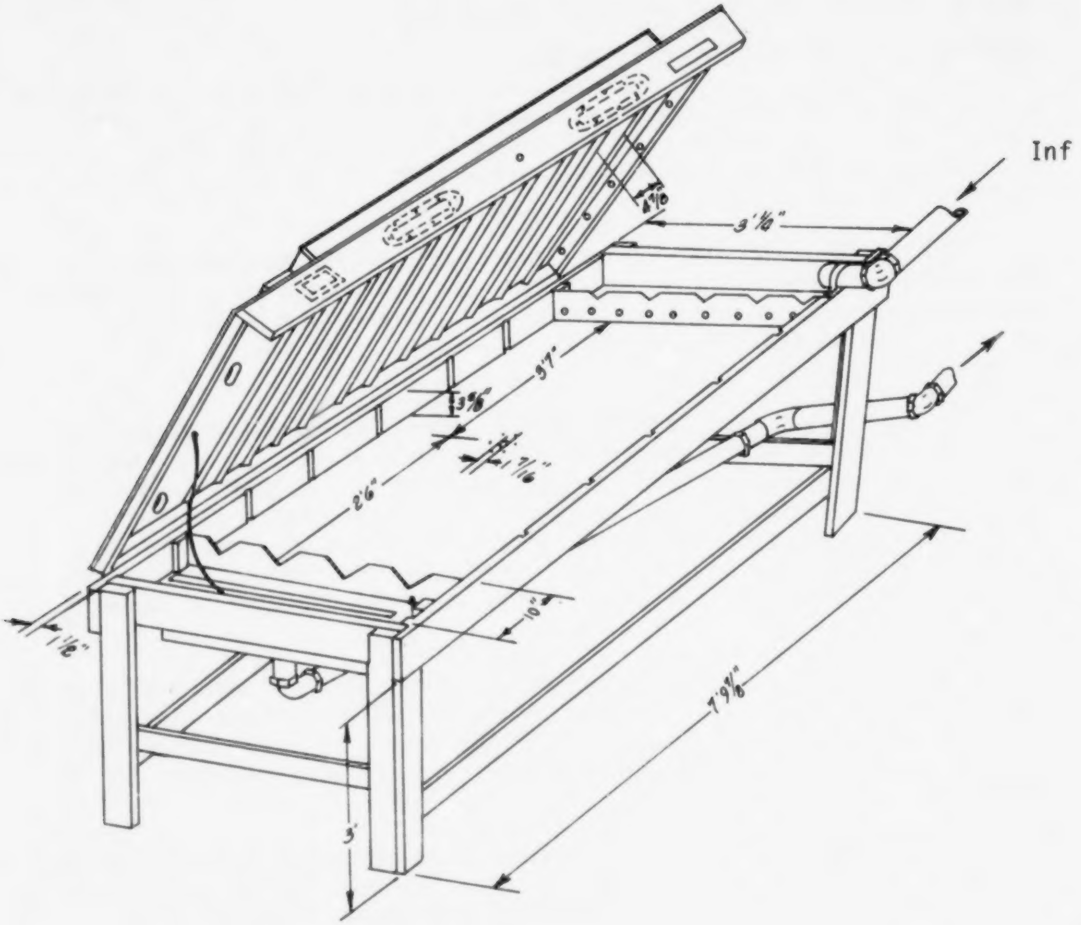

Inf
4 9/16
3'1/8"
9'7"
3 9/16"
1 7/16"
2'6"
10"
1 1/8"
7'9 3/4"
3'

Figure 4. Perspective drawing of the Kelly-Purdy Unit.

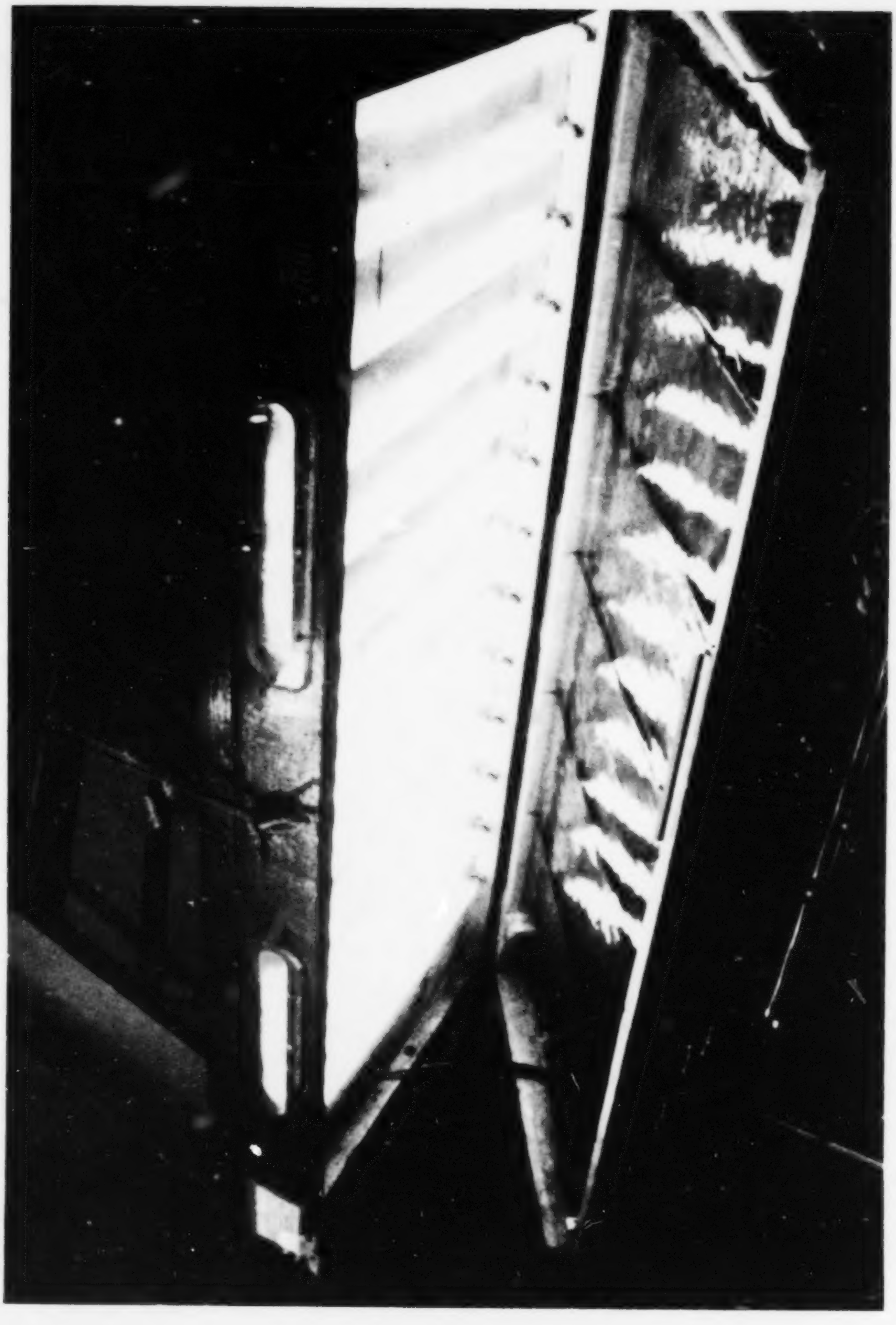


Plate 3. Photograph of the Kelly-Purdy Disinfection Unit.

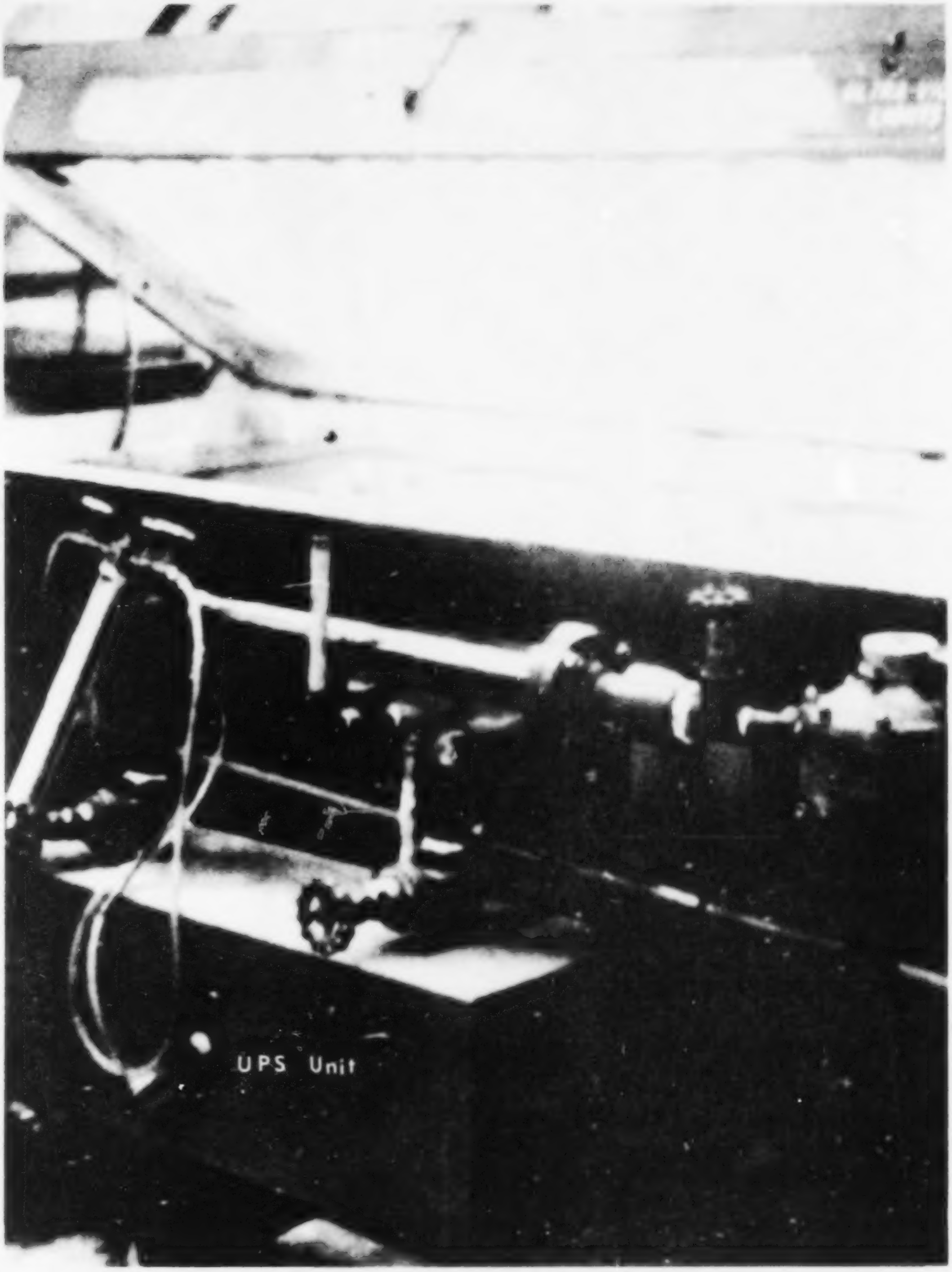


Plate 4. Photograph of the Kelly-Purdy and U.P.S. disinfection units.

SECTION 5

SAMPLING AND ANALYTICAL PROCEDURES

SAMPLING PROCEDURES

The sampling procedures described below were utilized for the duration of this research effort. Samples for routine wet chemistry analyses were collected by the operators on duty at the demonstration plant. Samples for microbiological analyses were collected by the staff microbiologist or microbiology laboratory assistants.

Routine Chemistry Samples

Samples for routine wet chemistry analyses were collected by the plant operators seven days a week at 1 AM, 5 AM, 9 AM, 1 PM, 5 PM, and 9 PM. Wide-mouth, half-pint plastic bottles were used for sample collection. These sample bottles were placed in a refrigerator until being transported to the laboratory, at which time they were composited by the staff chemists. Since the demonstration plant was operated at hydraulic steady-state, equal volumes (400 ml) of each of the six grab samples were used for the 24-hour composite sample.

Microbiological Samples

Either the staff microbiologist or the microbiology laboratory technicians collected all samples for microbiological evaluation. The samples were collected in 125 ml, wide-mouth glass bottles with glass stoppers that had been previously dry sterilized at 350°F for one hour.

ANALYTICAL PROCEDURES

The analytical procedures used in this research effort followed the 13th Edition of Standard Methods for the Examination of Water and Wastewater (6) insofar as practicable.

Flow

The influent flows to all unit processes, with the exception of the recarbonation basin, were measured by BIF/Brooks magnetic flow meters. This combination of meters and recorders proved to be relatively unreliable, and the City's instrumentation technicians lacked the expertise necessary to keep the flow meters properly calibrated and maintained. These problems resulted in the installation of several physical flow measuring elements (orifices, weirs, and venturi sections) such that accurate flow measurements could be obtained.

Biochemical Oxygen Demand

The procedure used for determining the five-day biochemical oxygen demand was as given in Section 219 of Standard Methods, and the dilution technique described in paragraph 4 (ii) was utilized.

Chemical Oxygen Demand

The following procedures were utilized to determine COD values on the routine samples. The low level technique was employed for those samples where the COD was expected to be less than 50 mg/l.

High Level Technique--

The procedure used was as described in Section 220 of Standard Methods.

Low Level Technique--

The COD of low level samples was determined by using the procedure given on page 19 of Methods for Chemical Analyses of Water and Wastes 1971. Two modifications were made to the procedure. The amount of mercuric sulfate was reduced from 1.0 to 0.4 grams, and the ferrous ammonium sulfate solution was 0.01 N instead of 0.025 N.

Total Organic Carbon

All total organic carbon determinations were made by using a Beckman Model 915 Total Organic Carbon Analyzer.

Total Residue

Total solids determinations were made in accordance with the procedure in Section 224A of Standard Methods.

Nonfilterable Residue

Total suspended solids determinations were made by employing the procedure in Section 224C of Standard Methods and using 2.4-cm diameter glass-fiber filters and Gooch crucibles.

Total Dissolved Solids

Total dissolved solids were computed by subtracting the nonfilterable residue from the total residue.

Total Phosphorus

The single reagent method given in Methods for Chemical Analyses of Water and Wastes 1971 was used for all total phosphorus determinations.

The amount of ammonium persulfate used was increased from 0.4 to 0.5 grams, and the amount of combined reagent was increased from 8 ml to 10 ml.

Ammonia Nitrogen

Ammonia nitrogen determinations were made by using an ion-specific electrode and the Known Addition Method. The electrode used was an Orion Model 95-10.

Total Kjeldahl and Organic Nitrogen

Total Kjeldahl nitrogen was determined by using an ion-specific electrode and the Known Addition Method after completing the digestion phase of the procedure given in Section 216 of *Standard Methods*. Organic nitrogen was determined by subtracting the ammonia nitrogen from the total Kjeldahl nitrogen.

Nitrite Nitrogen

Nitrite nitrogen determinations were made by using the procedure described in Section 134 of *Standard Methods*.

Nitrate Nitrogen

The phenoldisulfonic acid method, Section 213D of *Standard Methods*, was used to determine combined nitrite-nitrate nitrogen. Nitrate nitrogen was computed by subtraction of the nitrite nitrogen.

Sulfate

Sulfate was determined by an indirect atomic absorption spectroscopy method by adding a known concentration of barium chloride to form a barium sulfate precipitate. The barium concentration in solution was then determined by atomic absorption, and the sulfate concentration determined by subtraction.

Chloride

Chloride concentrations were determined by the mercuric nitrate method described in Section 112B of *Standard Methods*.

Alkalinity

Total and phenolphthalein alkalinity were determined by using the procedures given in Section 102 of *Standard Methods*.

Turbidity

Turbidity was determined by the nephelometric method described in Section 163A of *Standard Methods* with a Hach Model 2100A Turbidimeter. The standard references were formazin polymer suspensions.

Color

Color determinations were made by the plant operators by the use of a Hellige Aqua Tester and platinum-cobalt color disk.

Microbiological Determinations

Standard Plate Count--

Standard plate counts were performed as described in section 406 of Standard Methods. Plates were poured with Plate Count Agar (Difco) and incubated at 35°C ± 0.5° for 24 hours. Plates were counted on a Quebec colony illuminator with an American Optical electric counter.

Total Coliforms--

Total coliforms were determined by the following procedure:
(a) During the Kelly-Purdy portion of the project the membrane filter (MF) procedure was utilized with Gelman GN6 membranes. After a sample was filtered the membrane was placed on an absorbent pad saturated with M-ENDO Broth (Difco).

(b) During the remaining portion of the study the Most Probable Number (MPN) procedure was used, as described in Section 407E of Standard Methods. Lauryl Tryptose Broth (Difco) was inoculated and incubated at 35°C for 24 hours. Positive tubes were confirmed with Brilliant Green Bile Broth (Difco).

Fecal Coliform--

Fecal coliforms were measured by the following procedures:
(a) During the Kelly-Purdy portion of the study the MF method was used with Gelman GN6 membranes. Growth medium was MFC Broth (Difco).

(b) During the remainder of the project period a 5-tube, 4 dilution MPN procedure was used.

Virus Determinations

Stock--

The stock cultures used for the virus study were the Poliovirus Type I (vaccine strain), f2 Coliphage, and *E. coli* K12 (f^+) indicator cells.

Poliovirus Assay--

One- to four-liter samples were collected during the experimental runs in gas-sterilized flexible Cubitainers, capped, and placed in ice. The samples were shipped by air to Cincinnati in insulated boxes containing ice pre-frozen in water-tight quart-size Cubitainers. The shipments were picked up at the airport and taken to the National Environmental Research Center Cincinnati laboratory by EPA personnel. All samples (except sludge) were Swinny-filtered with 0.45 μ Millipore filter membranes treated with Tween 80 and then inoculated onto BGM (Barron Green Monkey Kidney tissue) cell lines using 0.5 ml in each of 4 bottles for each dilution. For sludge samples, approximately 200 ml of sample was centrifuged and a 15 gm portion of the centrate placed in a beaker. To this residue was added 40 ml of 10-percent buffered beef extract (Oxoid, Lab Lemco Powder, Flow Laboratory, Rockville, Maryland) which was mixed for 30 minutes on a magnetic stirrer, and then Swinny filtered with a 0.45 μ membrane. All of the filtrate was then inoculated onto BGM cell lines using 1 ml per bottle (approximately 40 bottles).

Coliphage Media--

The coliphage media consisted of three substances: Tryptone broth, tryptone overlay agar, and tryptone plating agar. The tryptone broth consisted of 10 gm/l of Tryptone(Difco 0123), 1.0 g/l of yeast extract (Difco 0127), 1.0 g/l of glucose, 8.0 g/l NaCl, and 0.22 g/l of $CaCl_2$. Tryptone overlay agar was the same as tryptone broth with the addition of 7.0 g/l of agar (Difco 0140). Tryptone plating agar was the same as tryptone broth with the addition of 15 g/l of agar. The salt diluent was 8.5 g/l NaCL and 0.22 g/l $CaCl_2$. Media and diluent sterilized by autoclaving at 15 psi and 121°C for 15 minutes. Glassware sterilized in a hot air sterilizer at 170°C for two hours.

Coliphage seed--

An overnight culture of E. coli K12 (f^+) was diluted 1:100 in one liter of tryptone broth. The culture was grown on a shaker at 37°C to an optical density of 0.2-0.3 which was approximately 10^8cells/ml. The culture was infected with f2 coliphage at a multiplicity of infection (MOI) of 3, and grown for 4-6 hours longer on the shaker. Twenty to thirty milliliters of chloroform were added and it was refrigerated overnight. The following day, the culture was centrifuged at 16,000 G for 20 minutes at 4°C to remove cellular debris. The supernatant yielded a stock suspension with a titer of at least 1×10^{11} pfu/ml.

Coliphage Assay--

Samples of 10 ml were collected and 0.5 ml chloroform was added immediately. The samples were stored in a refrigerator overnight. The next day, the following procedure was utilized. To sterile aluminum-capped tubes in a 47°C water bath, the following mixture was added: 2.5 ml molten tryptone overlay agar, 2.0 ml of E. coli K12 indicator cells diluted in tryptone broth to a concentration of 10^7cells/ml, and 0.5 ml of sample containing the phage or, if necessary, 0.5 ml of a 10-fold serial dilution. Salt diluent was used to make the sample dilutions. The tube contents were mixed on a vortex mixer. Contents were poured onto a petri plate containing 20 ml of solidified tryptone plating agar. The plate was swirled to evenly distribute the overlay agar and then allowed to solidify. The plates were inverted and incubated 18 hours at 37°C. Plaques were then counted and the titer calculated.

SECTION 6

OPERATION OF THE KELLY-PURDY UNIT

HYDRAULIC CHARACTERISTICS

Like other radiation processes, the kill obtained in the UV irradiation chamber was expected to be functionally dependent on the dose of ultraviolet light applied to the liquid flow. The theoretical UV dose can be computed by multiplying the theoretical residence time of the flow in the irradiation chamber by the average (arithmetic mean) UV intensity in the water being irradiated. Since considerable variation can exist between the theoretical and actual residence times in any unit process, the hydraulic characteristics of the UV irradiation chambers used during the study were of considerable importance. The occurrence of extensive short circuiting within the chamber would have had the effect of reducing the actual residence time at a given flow, which would have reduced the actual UV dose and resulted in higher bacterial densities in the radiated water.

Figure 5 is a graph that presents the theoretical residence time in the Kelly-Purdy irradiation chamber as a function of both flow and liquid depth. During most of this project the theoretical residence time for the Kelly-Purdy unit ranged from 0.4 to 2.0 minutes, while the depth was varied from 2.54 cm (1 inch) to 6.35 cm (2.5 inches). The majority of the research was conducted with the water depth at 2.54 cm and with flows of about 1.94 l/sec. (30 gpm), which resulted in an approximate exposure of 20 seconds.

Dye studies were performed at water depths of 2.54 cm (1 inch) and 6.35 cm (2.5 inches) to evaluate the residence time distribution functions (RTDF) of the system. Slugs of Rhodamine WT dye were injected into the influent flow to the Kelly-Purdy system, and samples of the effluent were collected and analyzed for relative dye concentration by using a Turner Model 111 Fluorometer. Flows of 0.31, 0.63, and 1.26 liters per second were used for the RTDF studies.

Figure 6 presents the RTDFs obtained at a water depth of 2.54 cm and the corresponding theoretical residence times (theoretical τ), and similar data for a flow depth of 6.35 cm(2.5inch) are shown in Figure 7. Actual residence time values can be evaluated by locating the centroid of the RTDF,as suggested by Morrill (7), and that procedure was used in the analysis of these data.

The residence times obtained from the RTDF's are significantly less

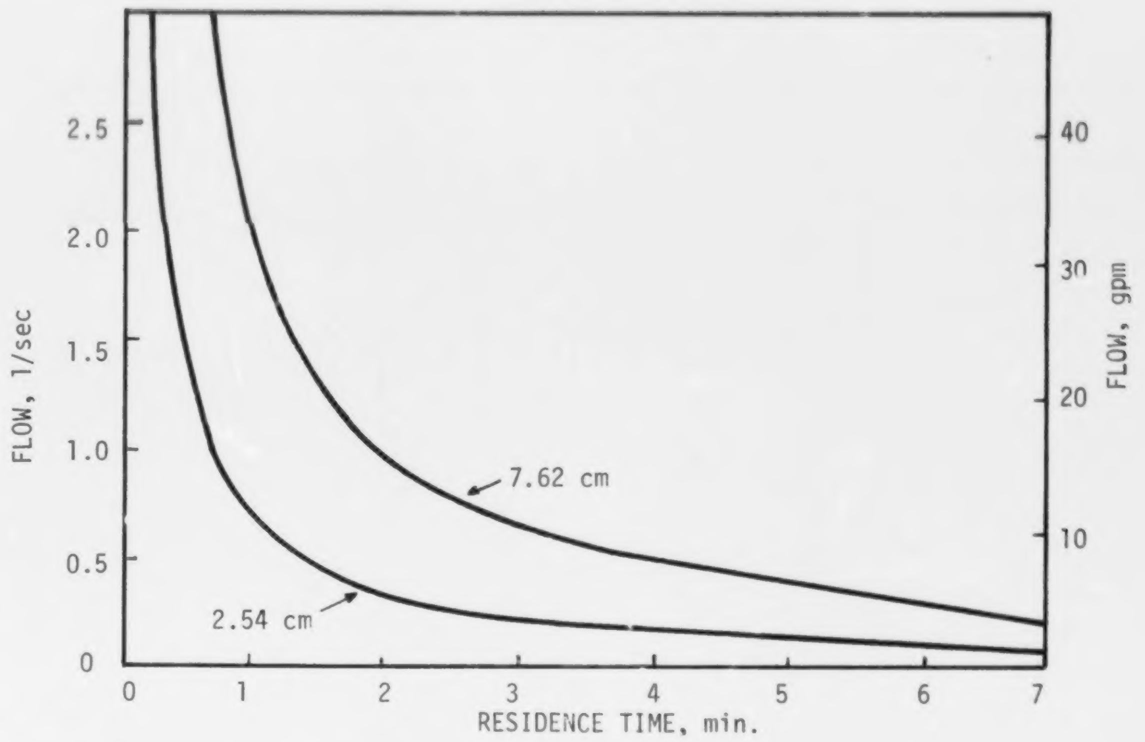


Figure 5. Theoretical residence time as a function of flow and depth for the Kelly-Purdy system.

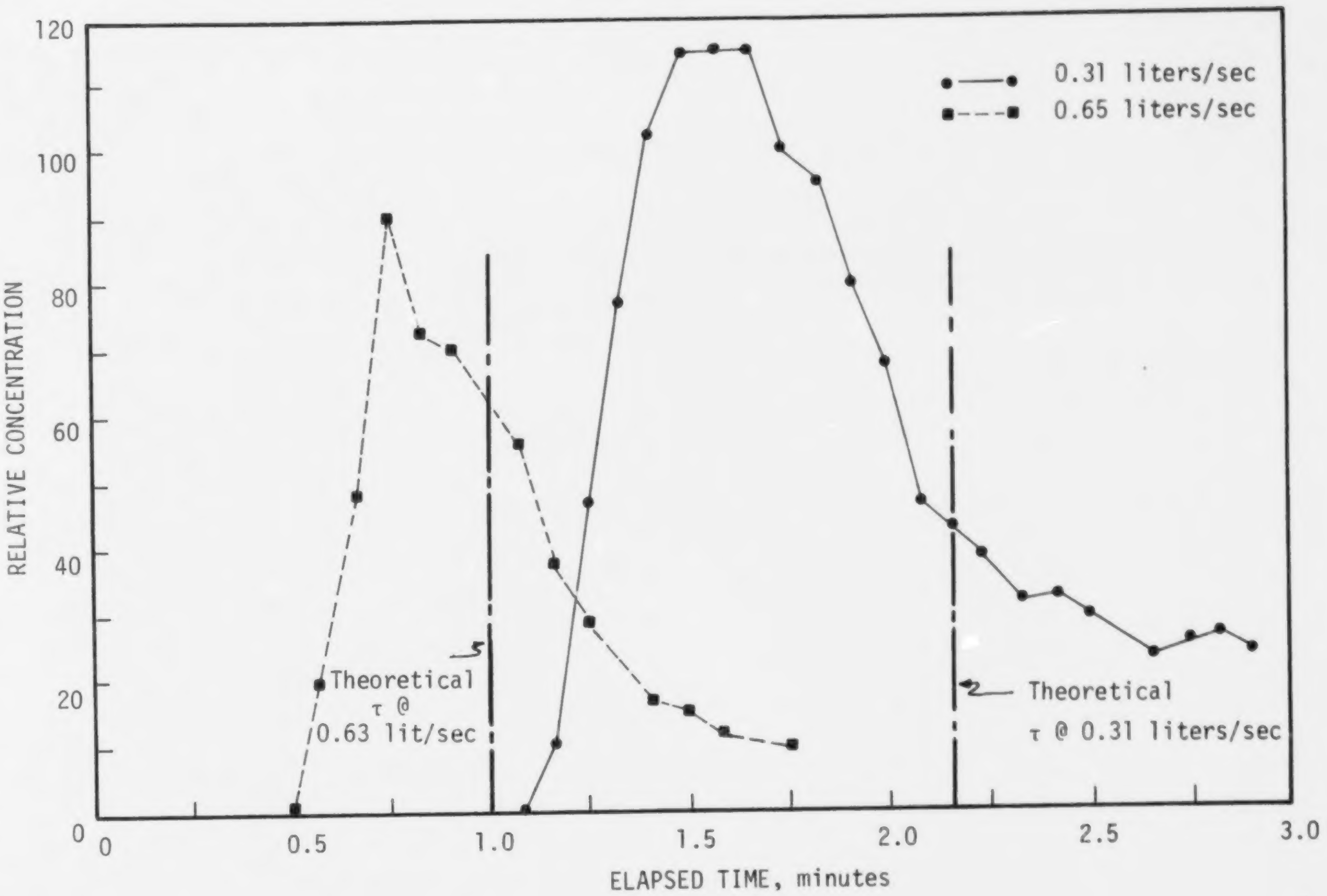


Figure 6. Residence time distribution functions obtained at a water depth of 2.54 cm in the Kelly-Purdy system.

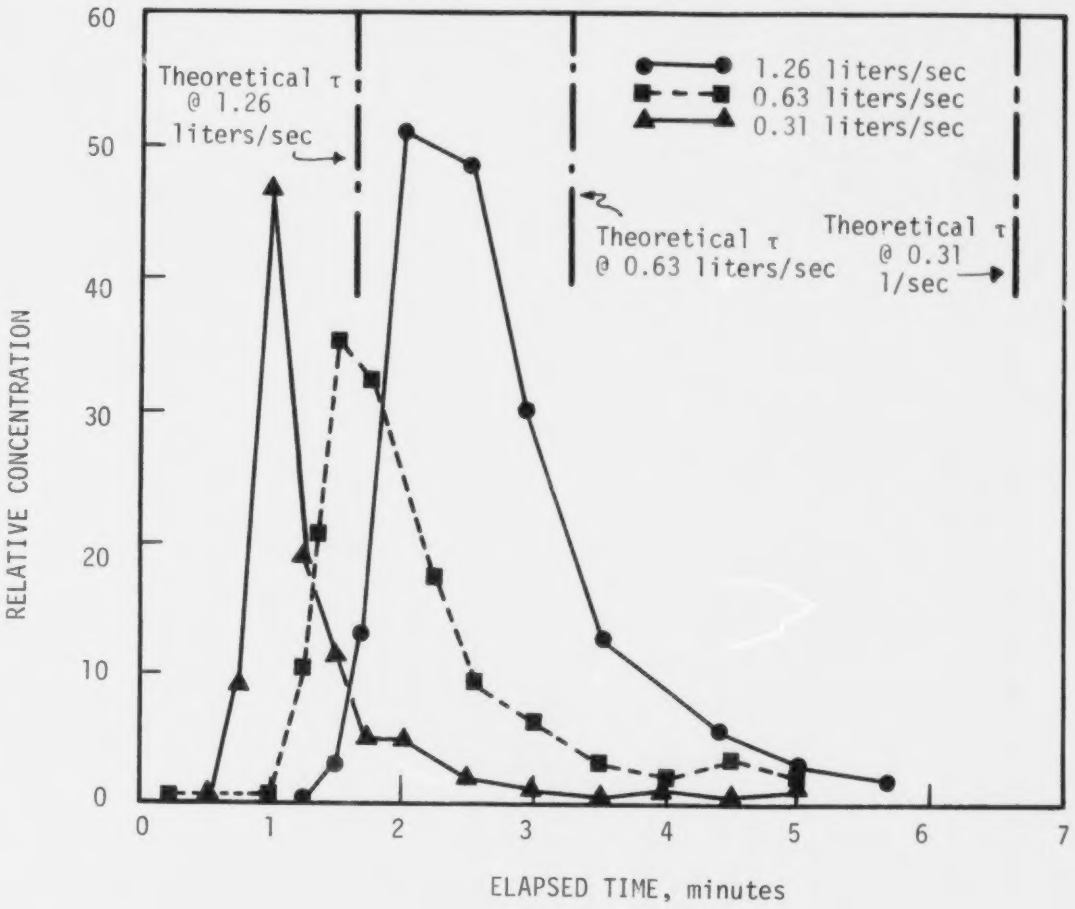


Figure 7. Residence time distribution functions obtained at a depth of 6.35 cm in the Kelly-Purdy system.

than the theoretical residence times. Figure 8 shows the ratio of the actual residence time to the theoretical residence time as a function of flow. It is both interesting and significant to notice that the difference between observed and theoretical residence times decreases as the flow increases. The most logical explanation for this is that the localized turbulence produced in the influent section of the unit at higher flows produces more uniform distribution across the transverse section, thus improving the hydraulic performance of the irradiation chamber.

It is important to notice that the Kelly-Purdy unit performs better hydraulically at the shallow depth, where the actual and theoretical residence times are in much better agreement than at the 6.35 cm depth.

Cumulative, dimensionless residence time distribution functions were computed for the dye studies as suggested by Thomas and Archibald (8). These curves are shown for the Kelly-Purdy unit in Figures 9 and 10. A tank which exhibited ideal plug-flow characteristics would produce a cumulative, dimensionless RTDF that was a horizontal line with zero recovery until the actual and theoretical residence times coincided. At $[t(1/\tau)]$ equal to 1.0 the curve would be vertical, and become horizontal with a dye recovery of 100 percent. Therefore good performance is indicated by a vertical line at 1.0; the more the curve exhibits an S-shape, the poorer the hydraulic performance of the system.

A comparison of the curves in Figures 9 and 10 indicates better performance at the shallower depth of 2.54 cm. The dye appears sooner and persists longer in the unit when the flow is at a depth of 6.35 cm.

INTENSITY AND DOSE DETERMINATIONS

Ultraviolet light intensity and dose data must be available if UV disinfection data are to be quantified. The intensity of the UV light at 254 nm was measured in the Kelly-Purdy unit with a Model IL500 Research Radiometer manufactured by International Light, Inc. The photodetector was calibrated by International Light, Inc., and a copy of the calibration certification was provided with the instrument.

Three intensity measurements were performed at various locations in the Kelly-Purdy unit. The results of the three separate intensity measurements are shown in Figure 11. The data in Figure 11 indicate the UV intensity at the water surface in the Kelly-Purdy unit. The computed mean intensity was 1190 μwatts/cm^2. Variation in these values was due to the geometry of the unit. The highest intensities were measured in the middle of the chamber.

During its passage through water UV light is attenuated, and the amount of light at any depth is assumed to be some function of the water depth, f(D). The function f(D) is usually taken as an exponential function of both water depth, D, and an extinction coefficient, k, and has the form shown below.

$$f(D) = I_o e^{-kD}$$

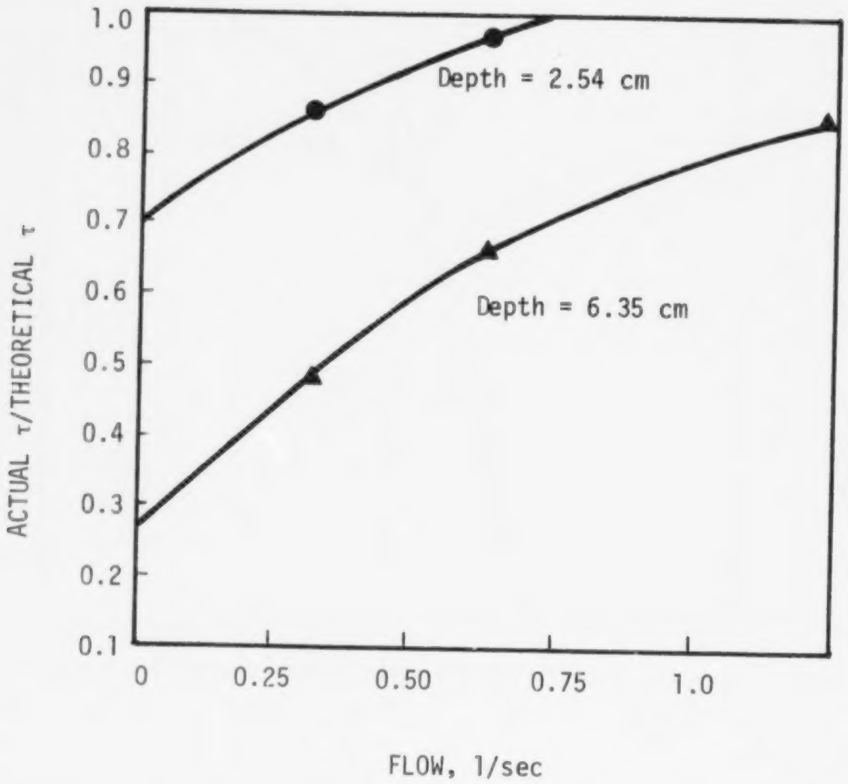


Figure 8. Ratio of actual to theoretical residence time for the Kelly-Purdy unit as a function of flow.

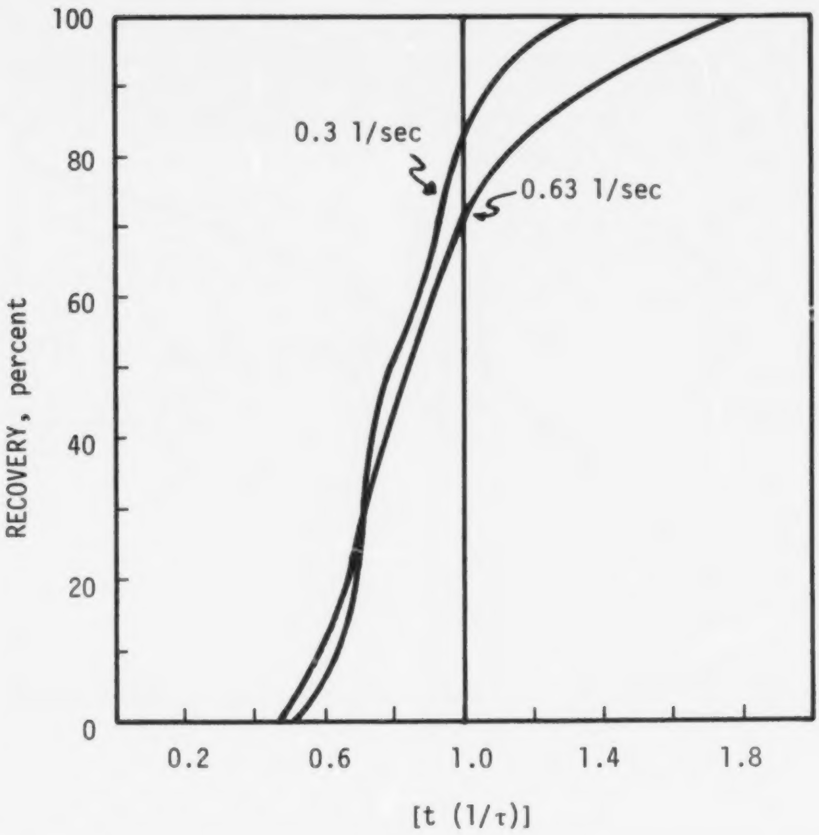


Figure 9. Dimensionless, cumulative residence time distribution function for the Kelly-Purdy unit (2.54 cm water depth).

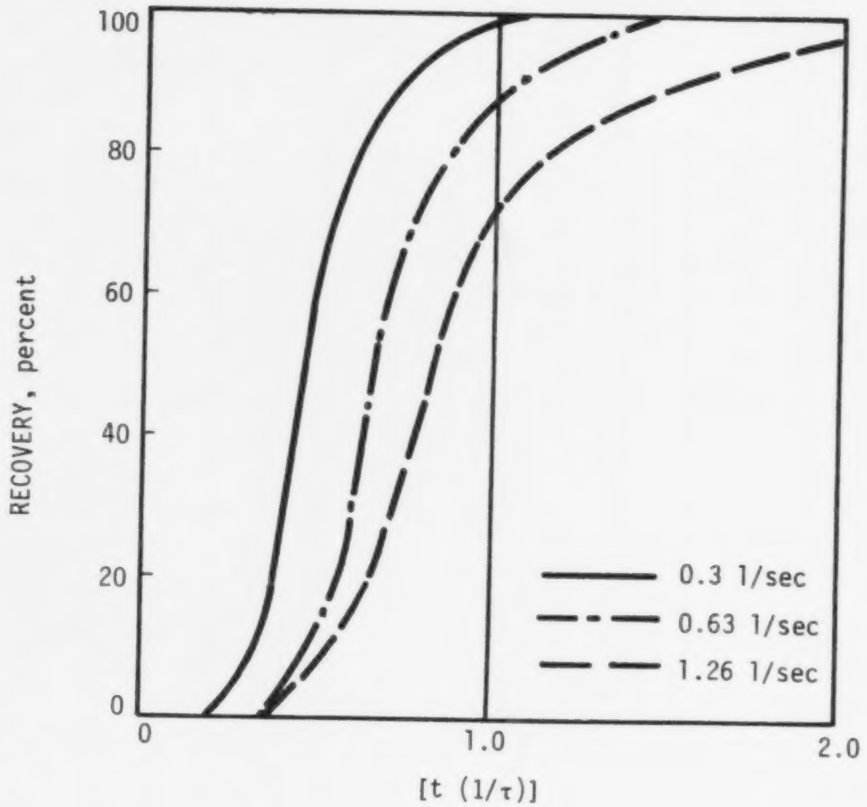


Figure 10. Dimensionless, cumulative residence time distribution function for the Kelly-Purdy unit (6.35 cm water depth).

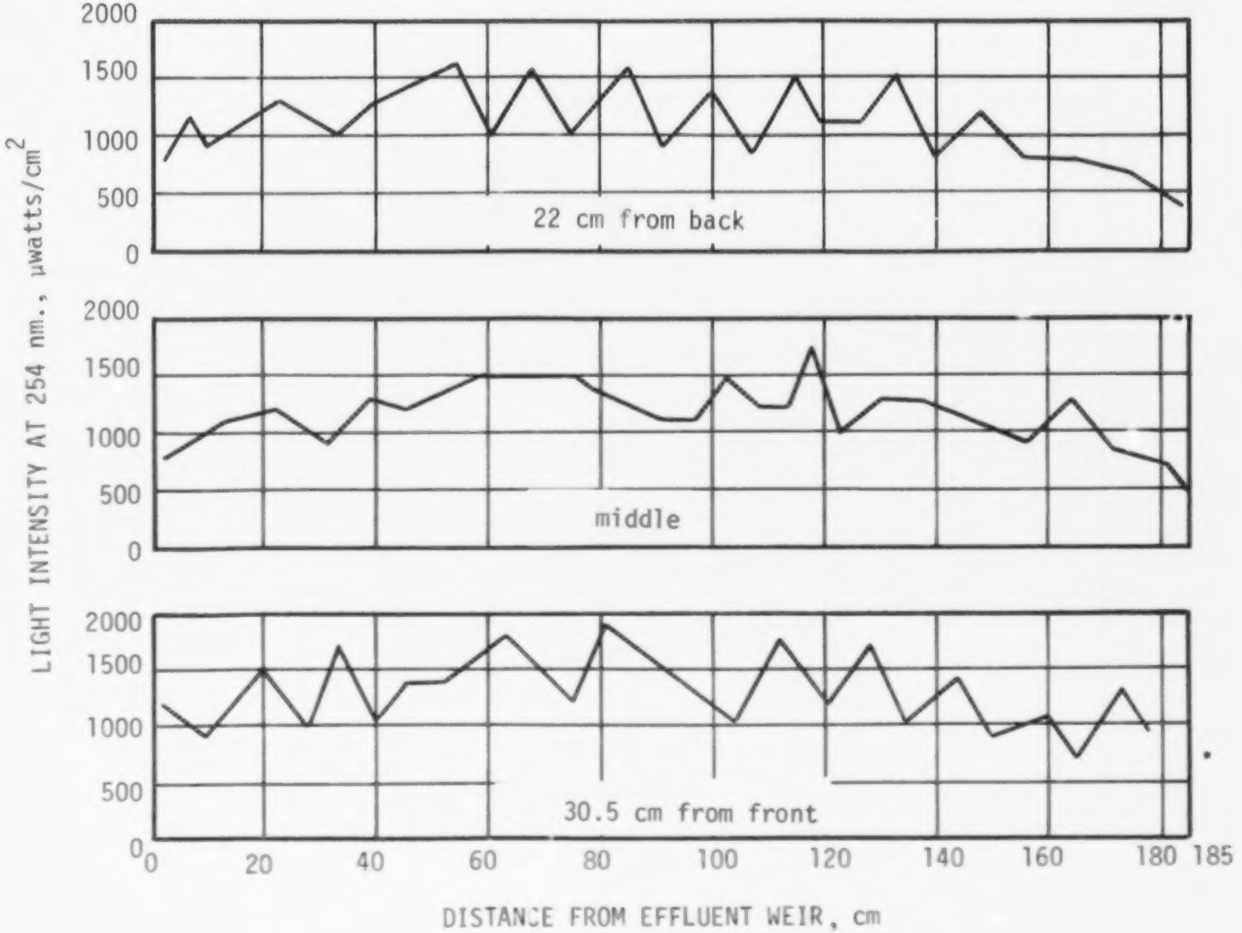


Figure 11. Measured UV light intensities at various locations in the Kelly-Purdy irradiation chamber.

I_0 is the surface intensity in watts/cm^2, k is the extinction coefficient with units of cm^{-1}, and D is the depth below the water surface in cm.

An average intensity in the water can be computed by integrating f(D) between the surface and the depth in question, and dividing by the water depth.

$$I_{avg} = \frac{\int_0^D f(D)dD}{D}$$

$$= \left[\int_0^D I_0 e^{-kD} dD \right] \div D$$

The above integration yields the equation shown below, which can easily be used to compute average intensity values.

$$I_{avg} = \frac{I_0 (1 - e^{-kD})}{kD}$$

Average intensity values were computed for the Kelly-Purdy Unit as a function of both depth and the extinction coefficient, k. These values are shown in Figure 12 as a family of curves for various values of k. A wastewater effluent with an extinction coefficient of about 0.5 cm^{-1} would cause a fifty-percent reduction in the average light intensity in a water depth of three centimeters.

A numerical value for the extinction coefficient, k, can be obtained experimentally by measuring the UV light intensity at different depths. Typical data are shown in Figure 13 for tap water, an activated sludge effluent, a filtered activated sludge effluent, and a filtered activated sludge effluent that had been passed through two activated carbon contactors. When these data are plotted on semi-log paper, the slope is the extinction coefficient.

The change in ultraviolet light transmissibility as a function of water quality is evident. The steeper the slope the higher the extinction coefficient, and thus the greater the attenuation. The activated sludge effluent had the highest extinction coefficient, while tap water had the lowest.

The direct measurement of an extinction coefficient is not always possible, and in many installations this could be a time consuming problem. It should be apparent that a relationship between the extinction coefficient

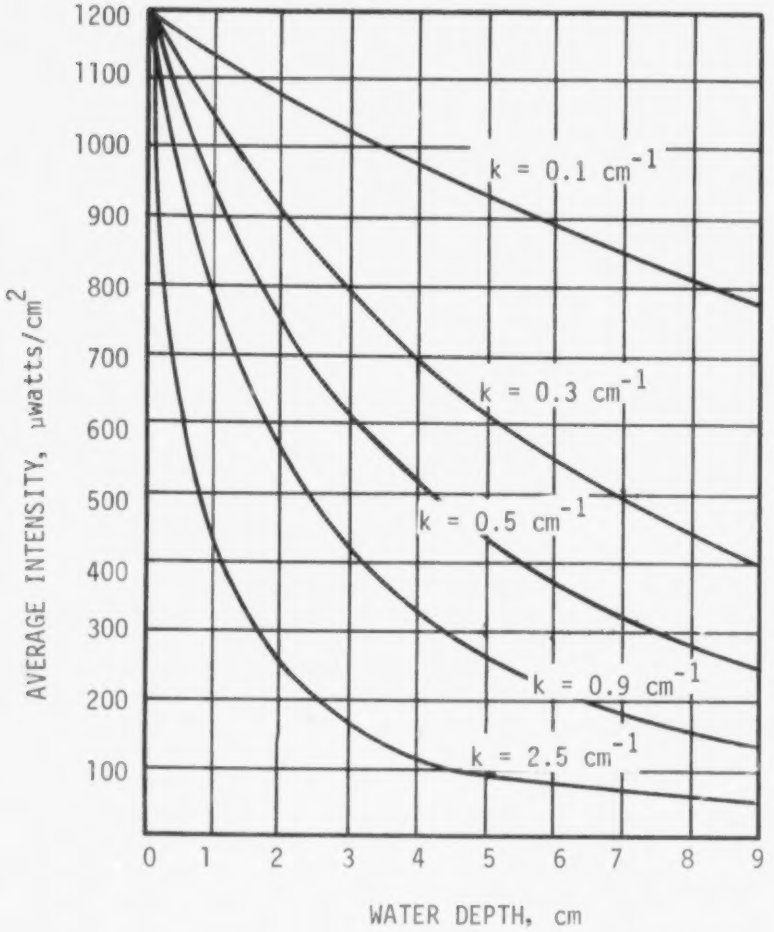


Figure 12. Average intensity of UV light as a function of water depth and the extinction coefficient.

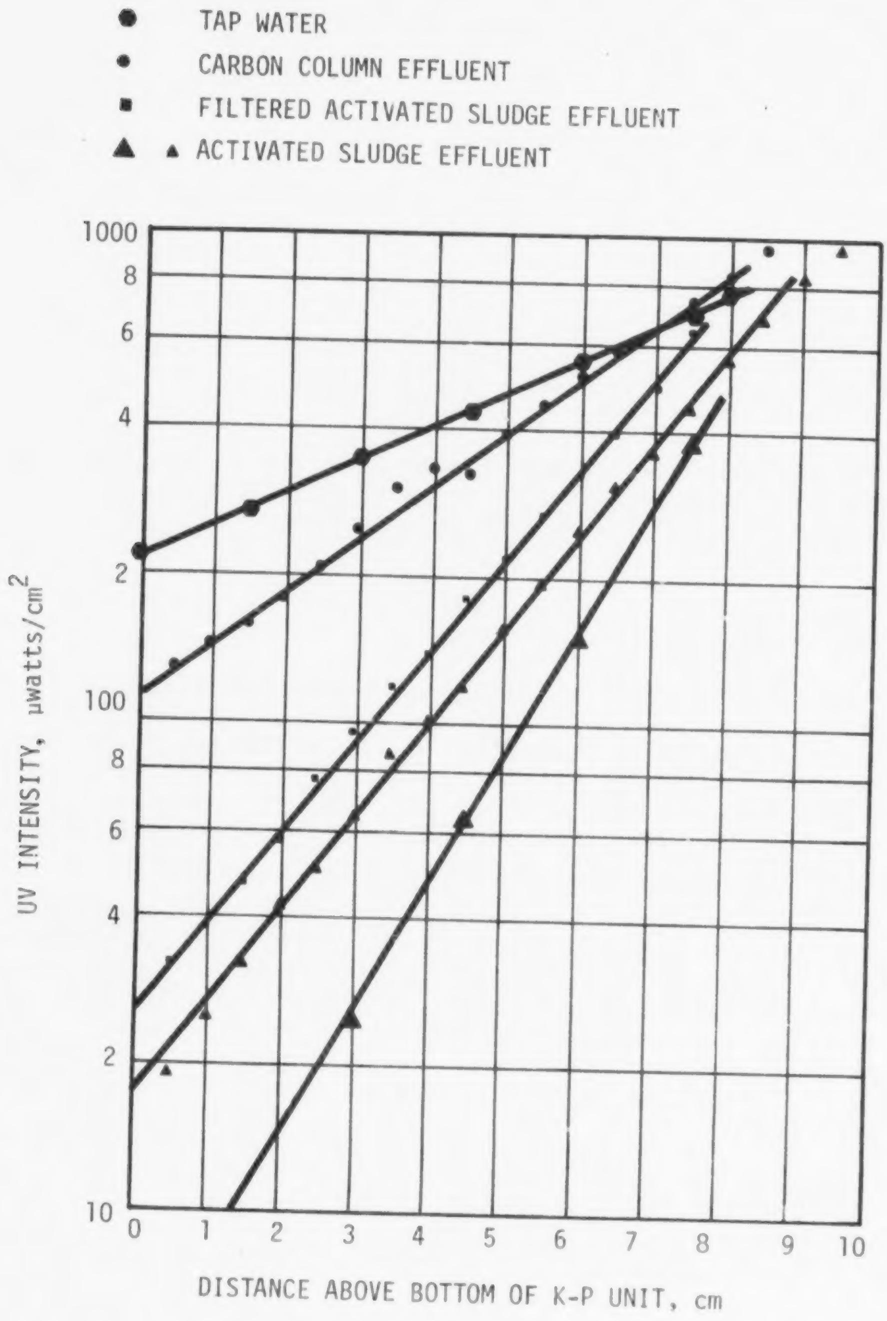


Figure 13. Typical data used to determine the extinction coefficient.

and the percent light transmittance exists. Using a previously defined relationship:

$$I=I_o\ e^{-kD}$$

but $\frac{I}{I_o}$ is the transmittance, T. Therefore,

$$T = \frac{I}{I_o} = e^{-kD}$$

and

$$\ln\left(\frac{I}{I_o}\right) = -kD$$

Most UV spectrophotometers used for measuring the transmittance of water samples have a path length of 1 cm. Therefore, the transmittance and extinction coefficient are related as shown below.

$$\ln T = \ln\left(\frac{I}{I_o}\right) = -k \qquad D=1$$

The above relationship is important in that transmittance data can be readily obtained on water samples if a spectrophotometer is available that can be used in the UV range. Several waters of varying quality were run through the Kelly-Purdy Unit, and the extinction coefficient and transmittance values determined. These data are shown in Figure 14 in conjunction with the theoretically predicted curve. The agreement between the experimental results and theory is excellent.

Dose determinations (i.e., the product of light intensity and residence time) can be made relatively easy if the average light intensity in the water is known, and if the actual residence time in the irradiation chamber is known. The previous discussion explained the relationships between intensity, transmittance, and the extinction coefficient. Additionally the RTDF's have defined the actual residence times as a function of flow. This information can be simplified and expressed graphically as shown in Figure 15.

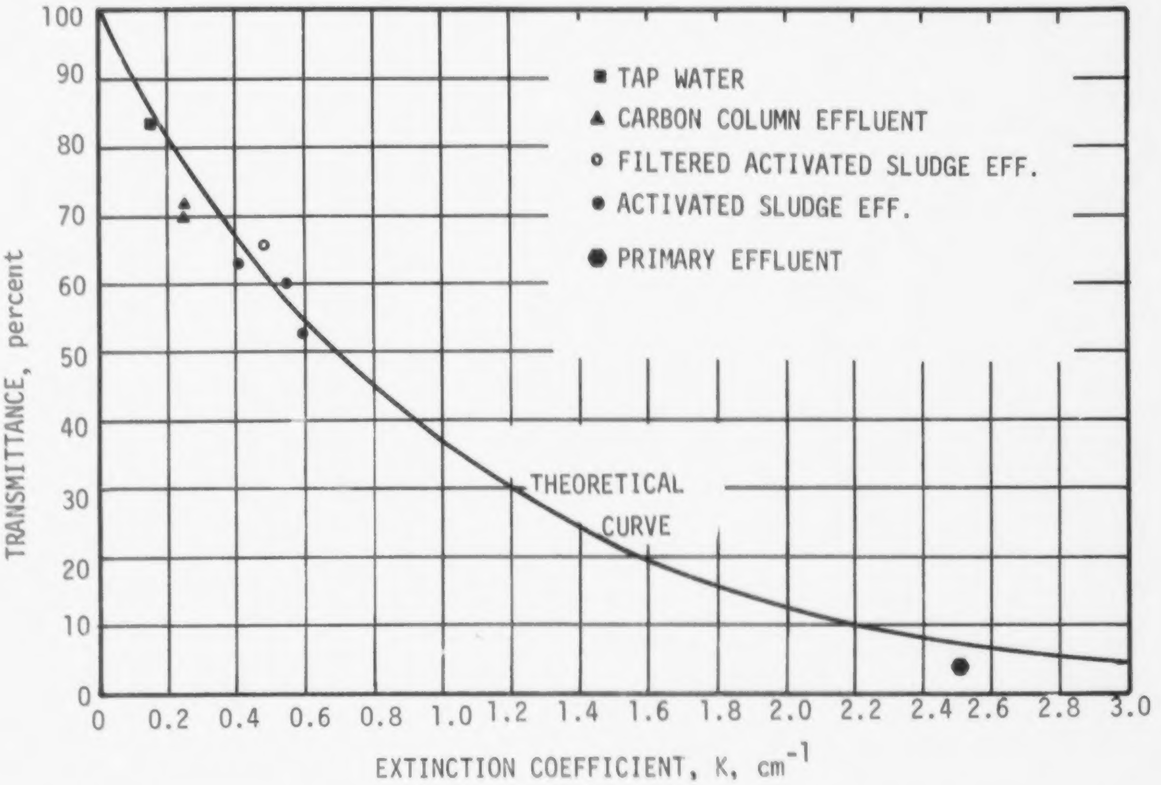


Figure 14. Comparison between the observed and theoretically predicted relationship of the extinction coefficient and transmittance.

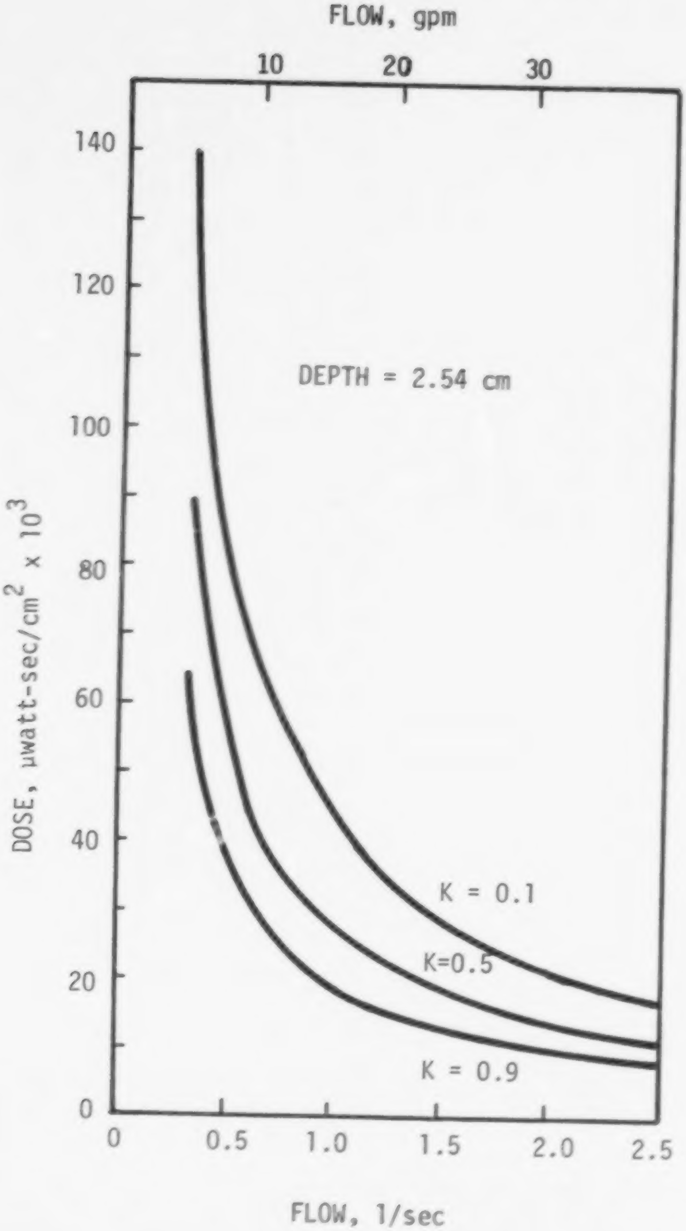


Figure 15. UV dose as a function of flow and the extinction coefficient for the Kelly-Purdy unit.

RUN NO. K1

Run No. K1 was a preliminary investigative activity that was conducted to provide basic data for project planning. The demonstration plant was configured as shown in Figure 16 for this study, in which 0.95 liters per second (15 gpm) of effluent from the No. 1 completely-mixed activated sludge system was pumped to the Kelly-Purdy UV Disinfection Unit. The remaining unit processes shown in Figure 16 were being utilized on other research projects.

On 26 July 1974 the twenty-four-hour composite sample for the activated sludge effluent had the following characteristics: TSS = 10 mg/l, COD = 42 mg/l, NH_3-N = 1.05 mg/l, Alkalinity = 105 mg/l as $CaCO_3$, soluble TOC = 9 mg/l, and pH = 7.1 units. These water quality criteria are typical of a relatively good quality activated sludge effluent, and microorganism reductions observed during this run should have been representative of the unit's disinfection capabilities.

During this study the Kelly-Purdy unit was operated with a water depth of 6.35 cm (2.5 inches), which resulted in a theoretical residence time of 1.8 minutes. Results of the disinfection study are shown in Table 7 and Figure 17.

The apparent increase in TSS is doubtless the result of sampling or analytical error, and is not supported by the more numerous turbidity data which indicate no significant change. A 2.29 log reduction was observed for the total coliforms, and a 2.25 log reduction was observed for the fecal coliforms.

The mean UV light intensity at the water surface was 1190 μ watt/cm^2, as previously described. During this period a UV spectrophotometer was not available; however, by assuming an average extinction coefficient of 0.5 the mean UV intensity in the irradiated water can be readily calculated to be 359 μwatts/cm^2. With a theoretical residence time of 1.8 minutes the resulting theoretical UV dose was 38,800 μwatt-sec/cm^2. The data presented in Figure 8 indicate that the ratio of actual to theoretical residence times was 0.77; therefore, the actual residence time and dose were 83 seconds and 29,900 μwatt-sec/cm^2.

Inadequate disinfection was obtained during this run. The quality of the activated sludge effluent being treated was good; yet disinfection was poor. Only a 2.25-log reduction in fecal coliforms was observed and at least 3.5-log reduction is usually necessary to satisfy the fecal coliform standard of 200 organisms per 100 milliliters.

UV transmittance data were not available at this stage of the project, so it is possible that the extinction coefficient was much higher than the estimated 0.5. The poor hydraulic characteristics of the unit when operated at the 6.35 cm depth did make a very significant difference in the UV dose, and this factor certainly affected the observed kills.

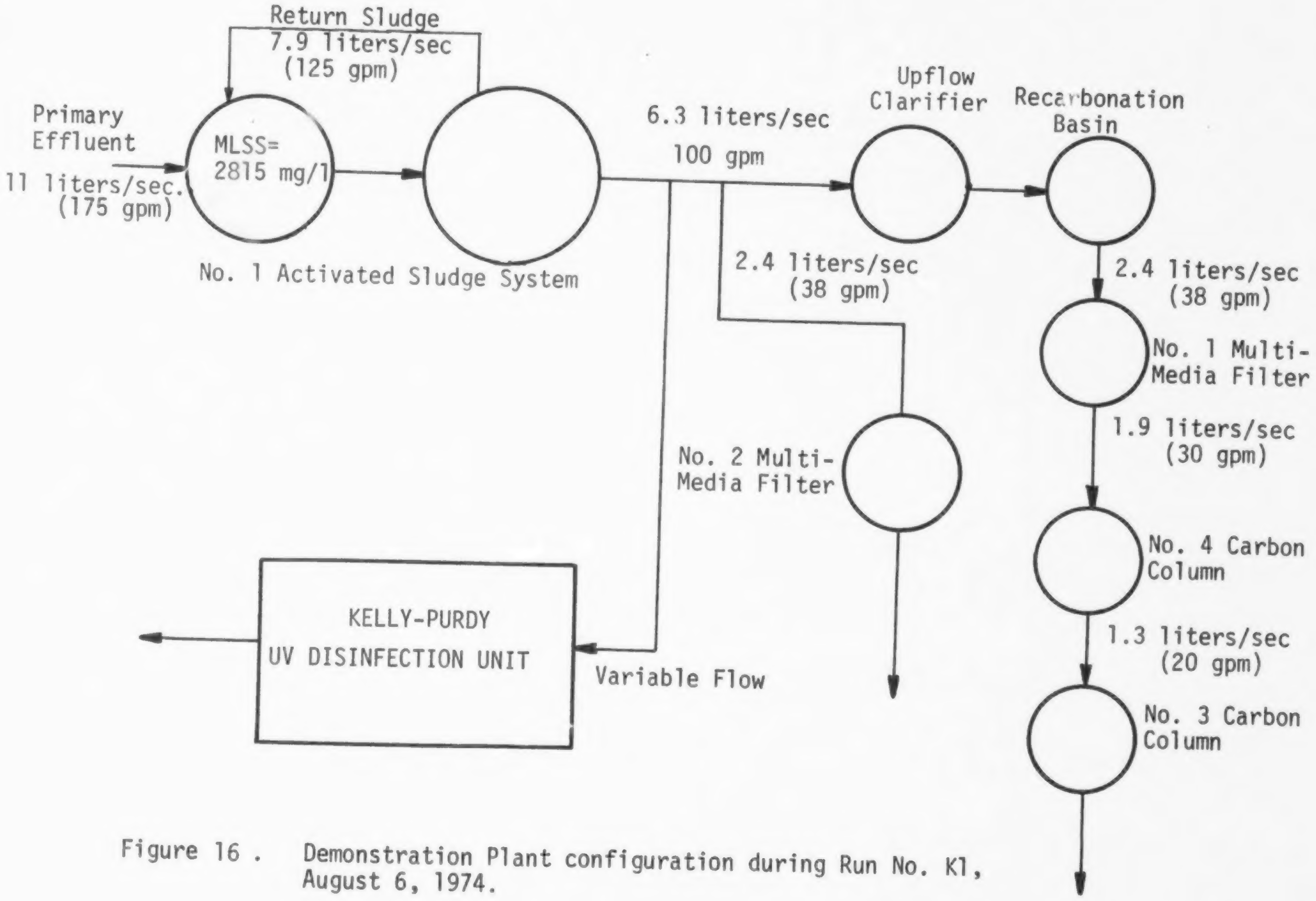

Return Sludge
7.9 liters/sec
(125 gpm)
Primary
Effluent
11 liters/sec.
(175 gpm)
MLSS=
2815 mg/l
No. 1 Activated Sludge System
6.3 liters/sec
100 gpm
Upflow
Clarifier
Recarbonation
Basin
2.4 liters/sec
(38 gpm)
No. 2 Multi-
Media Filter
2.4 liters/sec
(38 gpm)
No. 1 Multi-
Media Filter
1.9 liters/sec
(30 gpm)
No. 4 Carbon
Column
1.3 liters/sec
(20 gpm)
No. 3 Carbon
Column
KELLY-PURDY
UV DISINFECTION UNIT
Variable Flow

Figure 16 . Demonstration Plant configuration during Run No. K1, August 6, 1974.

TABLE 7. RESULTS OF RUN NO. K1, AUGUST 6, 1974

Parameter	Influent					Effluent					
	N	Min.	Max.	Mean[1]	Log of Mean[2]	N	Min.	Max.	Mean[1]	Log of Mean[2]	Mean Log[2] Reduction
TSS (mg/l)	1	-	-	13	-	1	-	-	26	-	-
Turbidity (NTU)	6	3.4	4.1	3.7	-	6	3.2	4.4	3.8	-	-
Standard Plate Count per ml	5	$1.5x10^5$	$3.3x10^5$	$2.3x10^5$	5.36	5	$1.4x10^3$	$2.7x10^3$	$1.8x10^3$	3.26	2.10
Total Coliforms per 100 ml	6	$3.7x10^6$	$6.2x10^6$	$5.3x10^6$	6.72	5	$1.0x10^4$	$6.0x10^4$	$2.7x10^4$	4.43	2.29
Fecal Coliforms per 100 ml	6	$2.5x10^5$	$6.5x10^5$	$4.3x10^5$	5.63	6	$1.0x10^3$	$5.0x10^3$	$2.4x10^3$	3.38	2.25

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

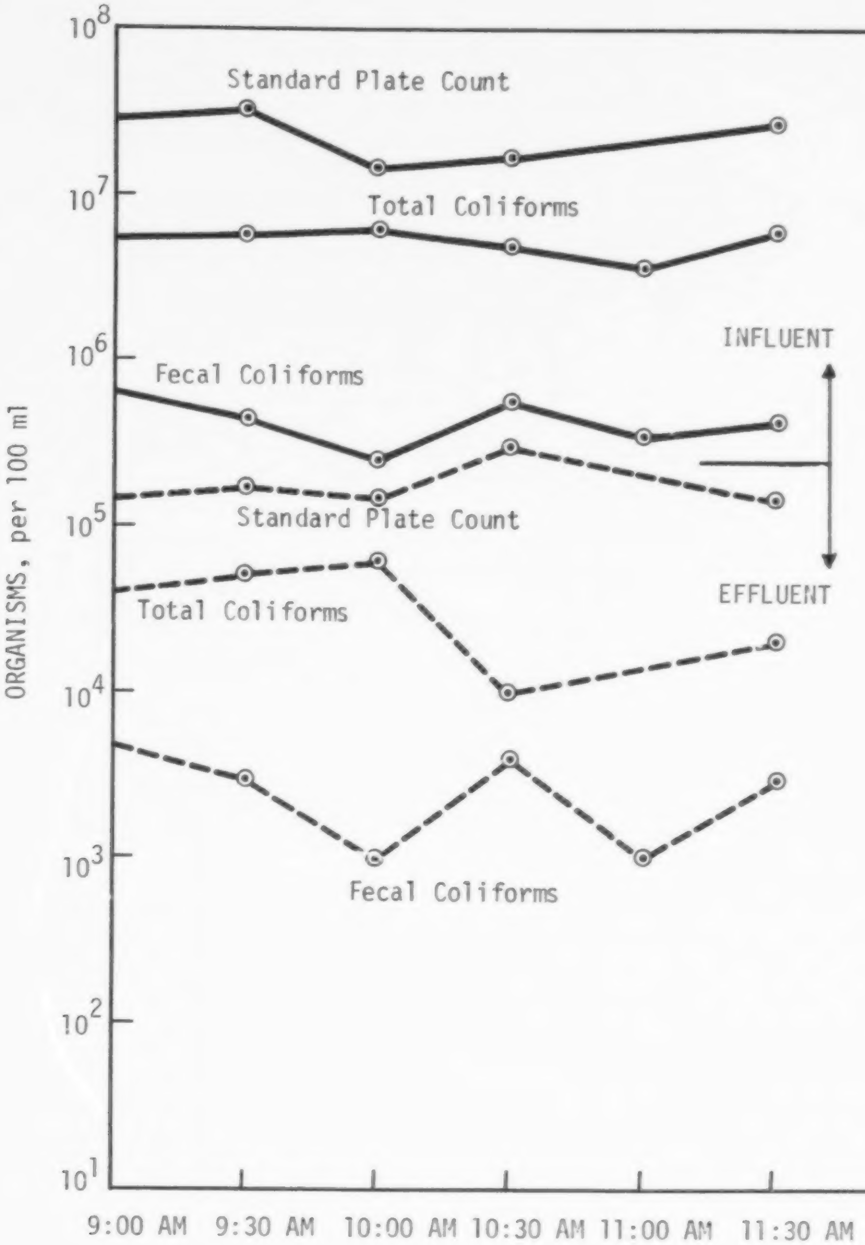


Figure 17. Results of Run No. K1, August 6, 1974.

RUN NO. K2

During Run No. K2 the Kelly-Purdy unit was operated on an activated sludge effluent at a flow of 0.72 l/sec, as shown in Figure 18. The depth of effluent in the exposure chamber was changed from 2.54 cm (1 inch) on September 28 to 5.08 cm (2 inches) to determine the effect of depth on disinfection. Additionally, the mean flow was varied from 0.32 l/sec (5 gpm) to 1.58 l/sec (25 gpm) to evaluate the effect of exposure time on disinfection.

The performance of the No. 1 activated sludge system during Run No. K2 is summarized in Table 8. Complete nitrification was desired at this time, but was not consistently achieved, as indicated by the 3.2 mg/l of ammonia nitrogen in the effluent. Effluent quality was very good if evaluated in terms of secondary treatment limitations. The computed reductions are based on the activated sludge influent stream, and not on the data for the raw wastewater entering the White Rock STP. The average BOD_5 and TSS of the raw wastewater were approximately 260 mg/l, which would yield reductions of 93 percent and 92 percent, respectively.

On 14 September 1974, the unit was operated at a depth of 2.54 cm (1 inch) and at flow rates of 1.6 l/sec (25 gpm) and 0.6 l/sec (10 gpm). Results of this operation are presented in Table 9. Examination of these data indicates that no significant difference in kill was observed at the two flow rates studied. Moreover, no significant difference in mean log reduction of total coliforms, fecal coliforms, and standard plate count organisms by ultraviolet light was observed.

The data for all of Run No K2 are summarized in Table 10. These data are for analyses performed on the grab samples collected for microbiological examination, and are not the routine process control samples for the Pilot Plant. During this run turbidity, total suspended solids, and color were relatively low, as were observed COD and TOC values.

The results of this portion of the disinfection study are presented graphically in Figure 19, 20, and 21, which are time-series plots of three microbiological water quality parameters. Examination of the plots indicate that the influent plate count densities were relatively constant during this run. Furthermore, no significant difference was evident in the disinfection obtained at the two depths studied.

Slightly less than a three-log reduction was observed for both total and fecal coliform organisms. This was inadequate for complying with the usual effluent limitation of 200 fecal coliform organisms per 100 ml, since the geometric mean fecal coliform density for Run No. K2 was 290/100 ml.

Most microbiological data obtained during the study of disinfection processes exhibit considerable variability, and more often than not an

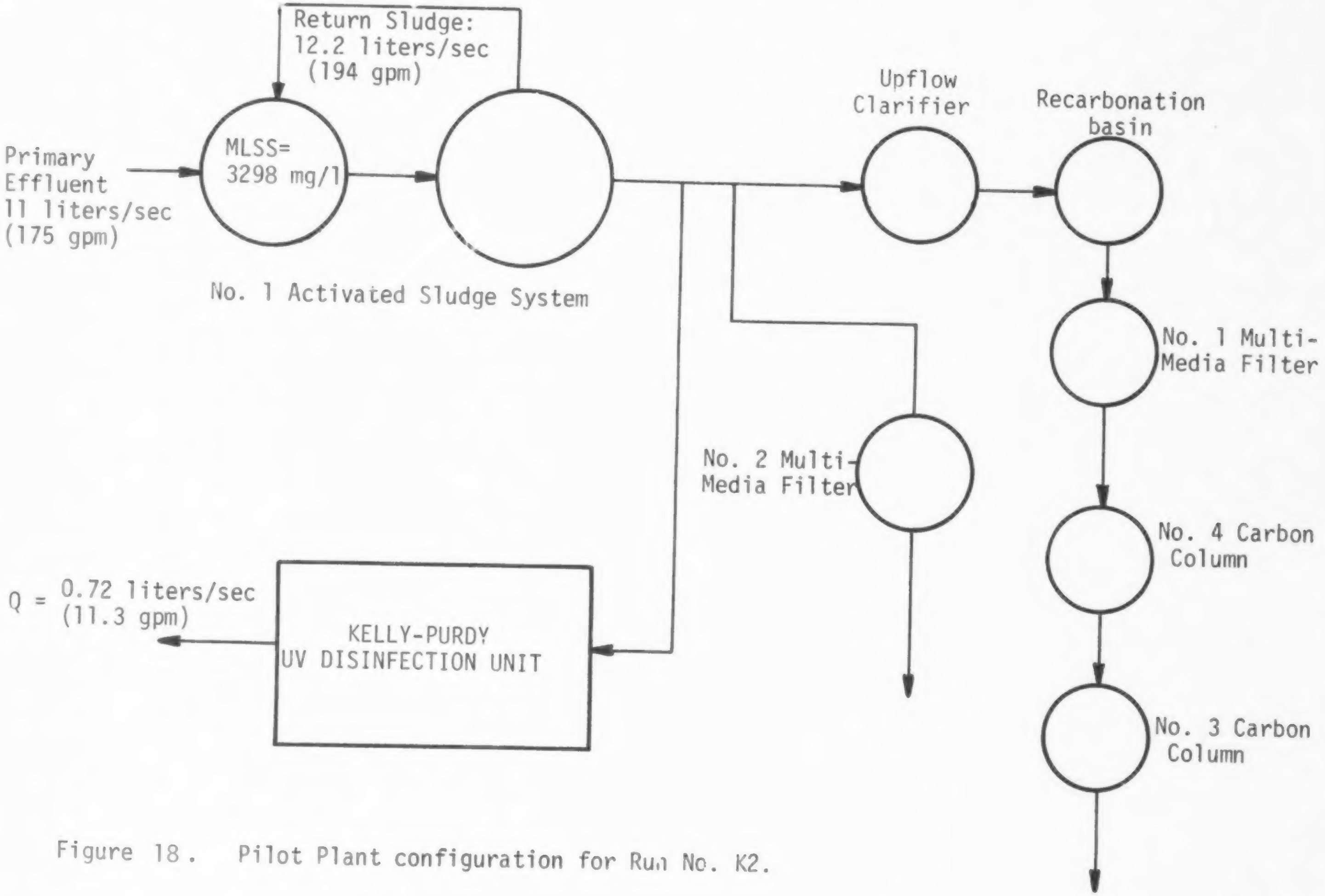

Return Sludge:
12.2 liters/sec
(194 gpm)
Primary
Effluent
11 liters/sec
(175 gpm)
MLSS=
3298 mg/l
No. 1 Activated Sludge System
Upflow
Clarifier
Recarbonation
basin
No. 1 Multi-
Media Filter
No. 2 Multi-
Media Filter
No. 4 Carbon
Column
No. 3 Carbon
Column
Q = 0.72 liters/sec
(11.3 gpm)
KELLY-PURDY
UV DISINFECTION UNIT

Figure 18. Pilot Plant configuration for Run No. K2.

TABLE 8. PERFORMANCE OF NO. 1 ACTIVATED SLUDGE SYSTEM DURING RUN NO. K2

Parameter	Activated Sludge Influent (mg/l)	Activated Sludge Effluent (mg/l)	Reduction (Percent)
TSS	127	21	83.5
BOD_5	126	18	85.7
COD	294	42	85.7
Sol. TOC	-	10	-
NH_3-N	16.0	3.2	80.0
Organic Nitrogen	11.0	4.5	59.1
NO_2 & NO_3-N	0.3	6.7	-
Total Nitrogen	27.3	14.4	47.3
Total P	8.2	6.1	25.6
Turbidity, NTU	-	3.9	-
Color, Pt-Co Units	-	39	-

TABLE 9. EFFECT OF FLOW RATE ON REDUCTION OF TOTAL COLIFORMS, FECAL COLIFORMS, AND STANDARD PLATE COUNT BY ULTRAVIOLET LIGHT (SPECIAL STUDY OF SEPTEMBER 14, 1974).

Parameter	FLOW 1.6 l/sec Influent	 Effluent	 Value	 0.6 l/sec Influent	 Effluent
Total Coliforms per 100 ml	$8.5x10^6$	$3.6x10^4$		$5.7x10^6$	$4.1x10^4$
	$7.8x10^6$	$3.0x10^4$		$7.5x10^6$	$4.3x10^4$
	$6.8x10^6$	$4.4x10^4$		$6.2x10^6$	$3.2x10^4$
	$7.7x10^6$	$3.6x10^4$	Mean	$6.4x10^6$	$3.8x10^4$
	6.89	4.56	Log of Mean	6.81	4.58
	2.33		Mean Log Reduction	2.23	
Fecal Coliforms per 100 ml	$1.36x10^6$	$4.8x10^3$		$2.16x10^6$	$5.1x10^3$
	$1.12x10^6$	$6.5x10^3$		$1.12x10^6$	$8.1x10^3$
	$1.39x10^6$	$4.8x10^3$			$6.4x10^3$
	$1.28x10^6$	$5.3x10^3$	Mean	$1.55x10^6$	$6.4x10^3$
	6.11	3.72	Log of Mean	6.19	3.81
	2.39		Mean Log Reduction	2.38	
Standard Plate Count per 100 ml	$4.1x10^5$	$1.4x10^3$		$2.2x10^5$	$9.6x10^2$
	$4.9x10^5$	$1.4x10^3$		$3.1x10^5$	$1.7x10^3$
	$6.6x10^5$	$1.14x10^3$			$1.4x10^3$
	$5.1x10^5$	$1.3x10^3$	Mean	$2.6x10^5$	$1.3x10^3$
	5.71	3.11	Log of Mean	5.41	3.11
	2.60		Mean Log Reduction	2.30	

TABLE 10. RESULTS OF RUN NO. K2

Parameter	Influent					Effluent					
	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean	Mean Log Reduction[2]
TSS (mg/l)	11	2	14	7	-	11	1	18	10	-	-
Turbidity (NTU)	11	1.0	7.6	3.9	-	12	2.5	7.5	5.1	-	-
Standard Plate Count per ml	17	4.2×10^4	4.5×10^5	8.4×10^4	4.92	15	1.5×10^2	1.5×10^3	4.7×10^2	2.67	2.25
Total Coliforms per 100 ml	18	2.4×10^4	8.3×10^6	8.4×10^5	5.92	16	2.2×10^1	4.0×10^4	1.0×10^3	3.00	2.92
Fecal Coliforms per 100 ml	18	2.4×10^4	1.1×10^6	2.3×10^5	5.36	15	4.0×10^1	9.3×10^3	2.9×10^2	2.46	2.90

---

[1] Geometric means are reported for all micorbiological data.

[2] Reported for micorbiological data only.

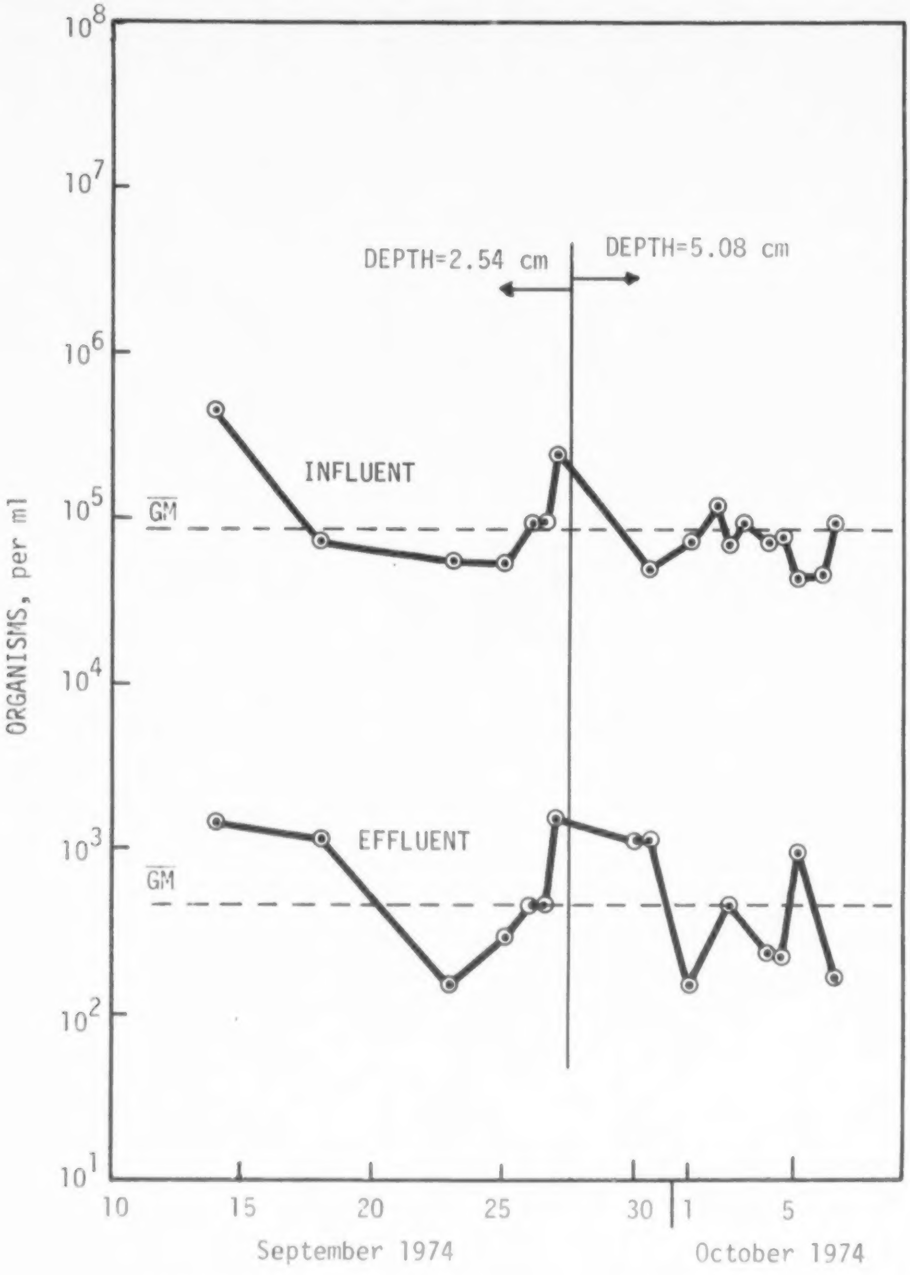


Figure 19. Standard plate count data for Run No. K2.

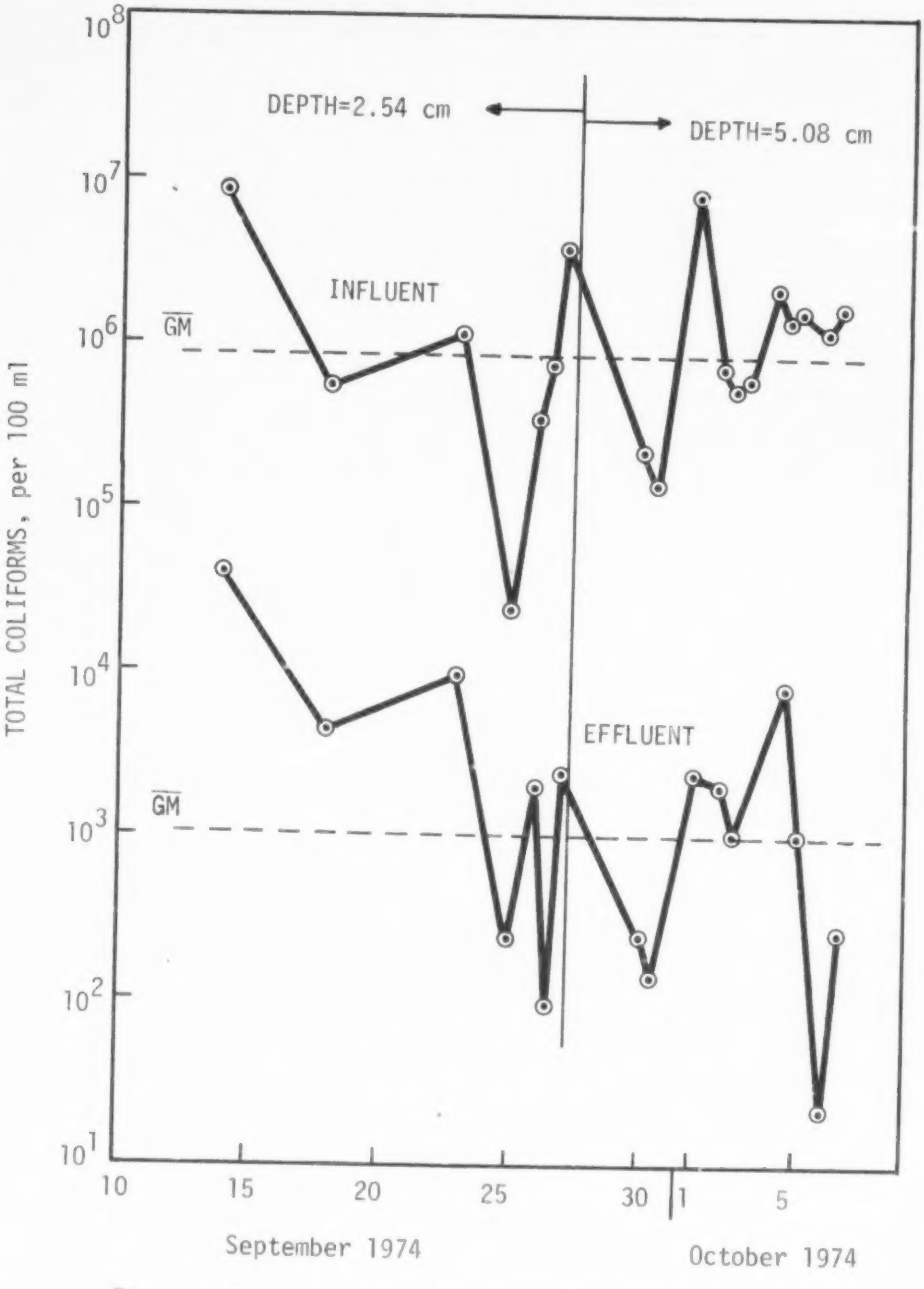


Figure 20. Total Coliform data for Run No. K2.

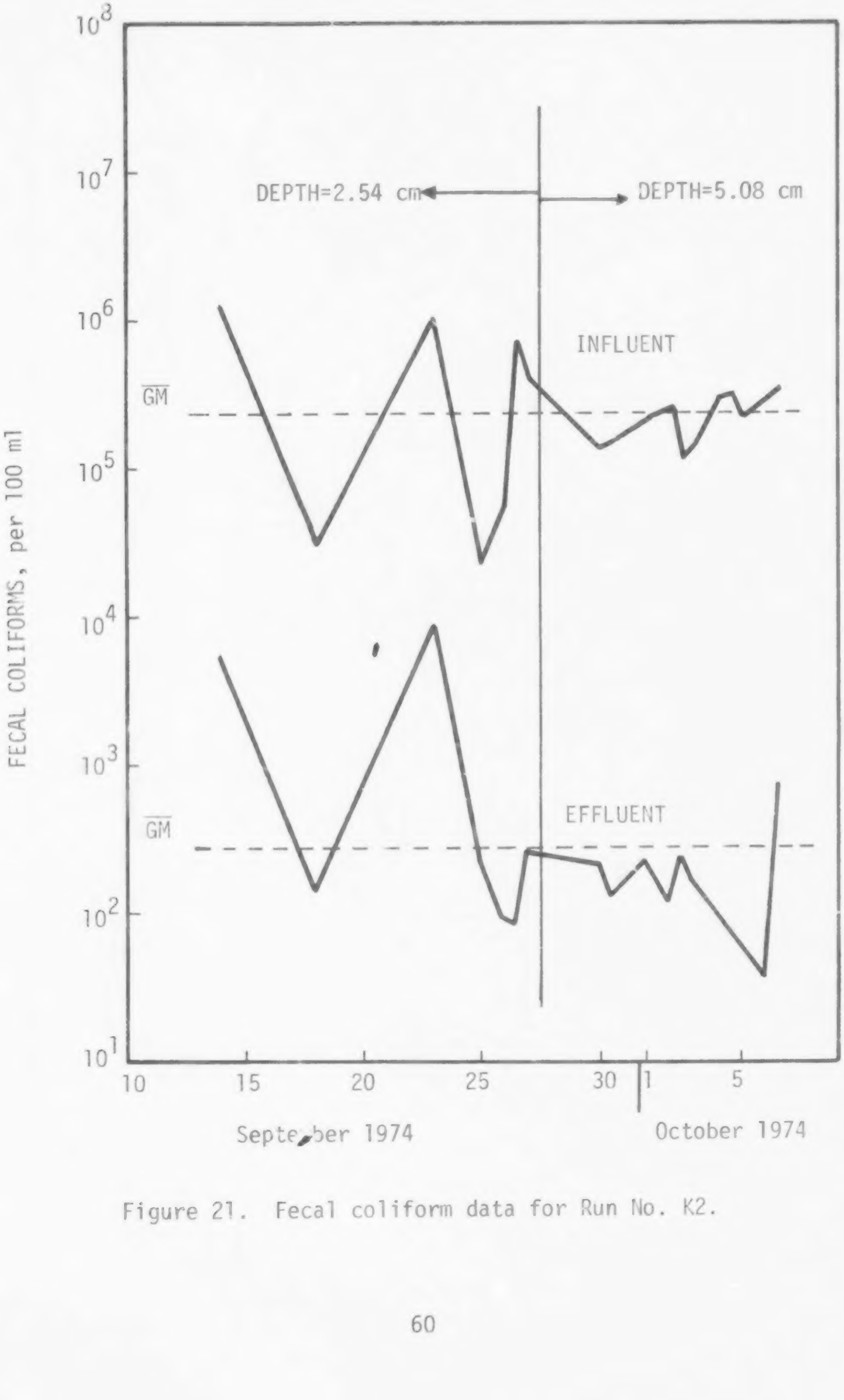


Figure 21. Fecal coliform data for Run No. K2.

occasional high value will be observed for no readily explainable reason. One must assume that the data are representative of the process performance, and not the result of poor laboratory technique. The occurrence of sporadic high numbers in microbiological data is the reason that the geometric mean is used as a relative indicator of the representative organism density instead of the arithmetic mean.

During the analysis of these data several different statistical procedures were employed to evaluate the consistency or reliability of the ultraviolet light disinfection process. All of these data were characteristically skewed toward the higher side, and histograms clearly showed tailing toward higher values.

One particular statistical procedure that has been used by the authors and many other researchers to evaluate process reliability is the plotting of the frequency distribution, or the probability distribution function of the data. In this type of data analysis, the individual data are ranked from highest to lowest, and the probability of each element being equalled or exceeded by the remaining data is computed. The value of each element in the data file is then plotted as the ordinate, and the corresponding probability is plotted as the abcissa.

The objective of this analysis is to obtain a straight-line plot, such that the prediction of events with a very low probability of occurrence is facilitated. Several different probability distribution functions can be used to establish the scale for the abcissa. The normal or Gaussian distribution is most commonly used, and this type of graph paper is commercially available; however, only those data which are normally distributed plot as a straight line.

The log normal distribution will tend to straighten those data skewed to the higher values, and this function has been used with considerable success in plotting effluent data from wastewater treatment plants.

The Type I asymptotic extreme-value distribution of largest values, most commonly called the Gumbel distribution (9,10), has been extensively used by hydrologists to predict rare flood events. For an in-depth discussion of the statistics involved,the reader should consult a good hydrology text, or a civil engineering statistics text.

During this project the normal, log normal, and extreme-value frequency distributions were all tested, and the Gumbel extreme-value frequency distribution consistently provided the most satisfactory graphical analysis. The Gumbel plots are shown for Run K2 in Figures 22 through 24.

The one percent probability level indicates the value which will be equalled or exceeded approximately four times per year, while the 0.1 percent probability value will be equalled or exceeded once every 2.7 years, in theory. Additionally, Figure 24 indicates that the fecal coliform density of 200 per 100 mls will be equalled or exceeded in sixty (60) percent of the samples collected.

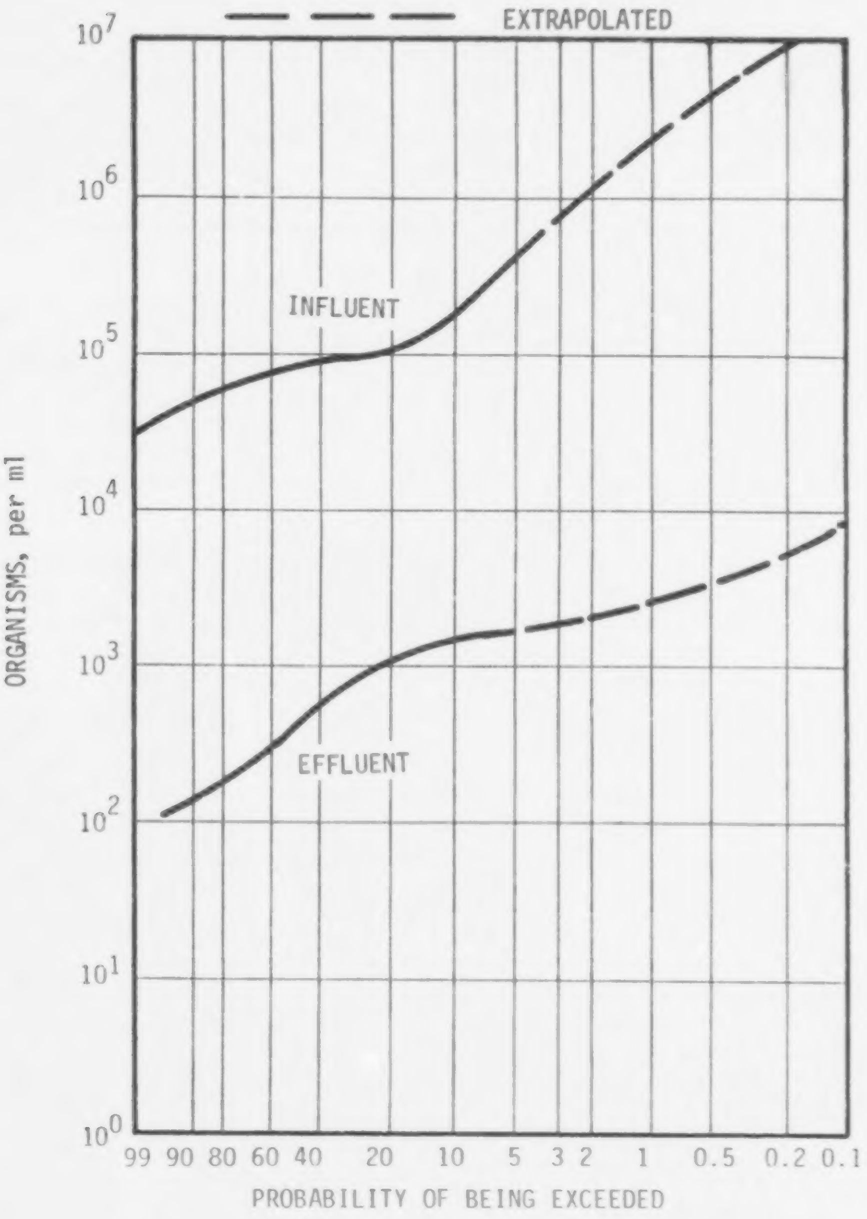


Figure 22. Extreme-value frequency distribution for standard plate count data, Run No. K2.

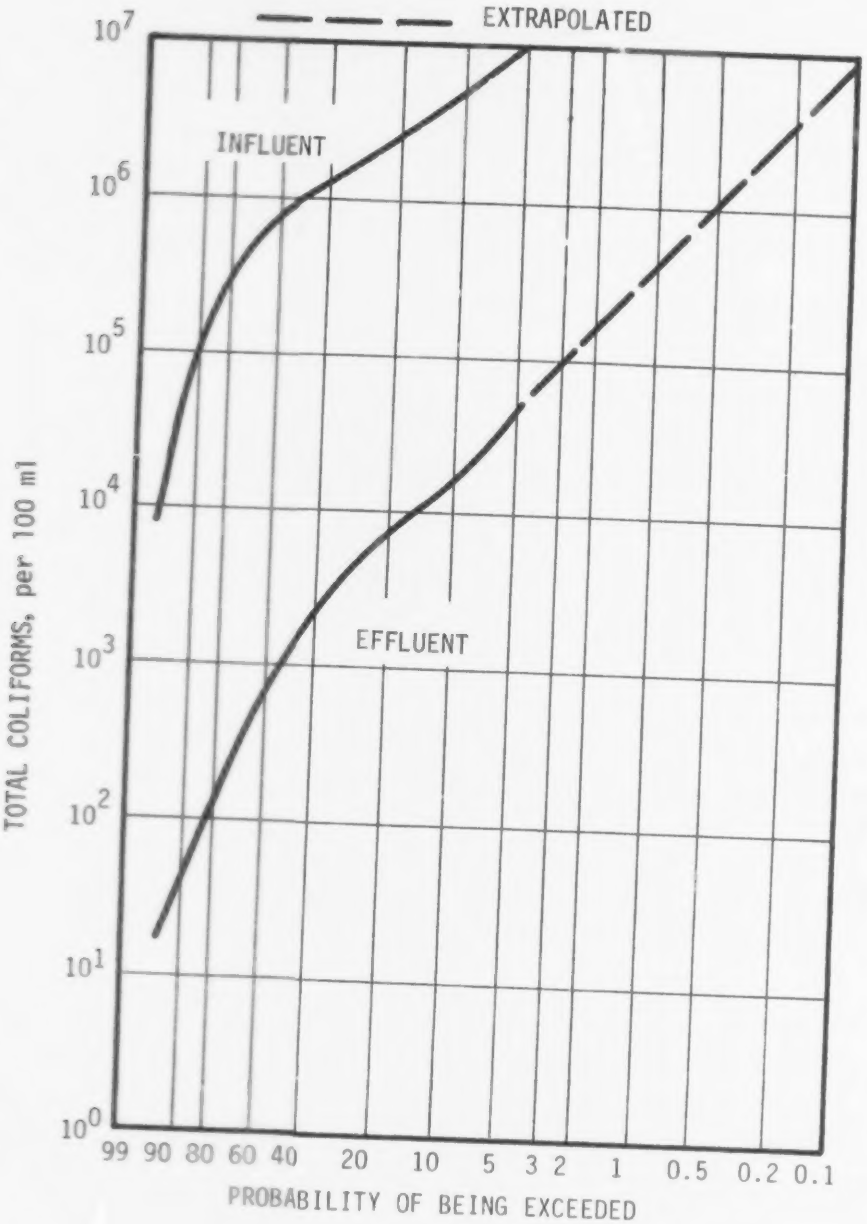


Figure 23. Extreme-value frequency distribution for total coliform data, Run No. K2.

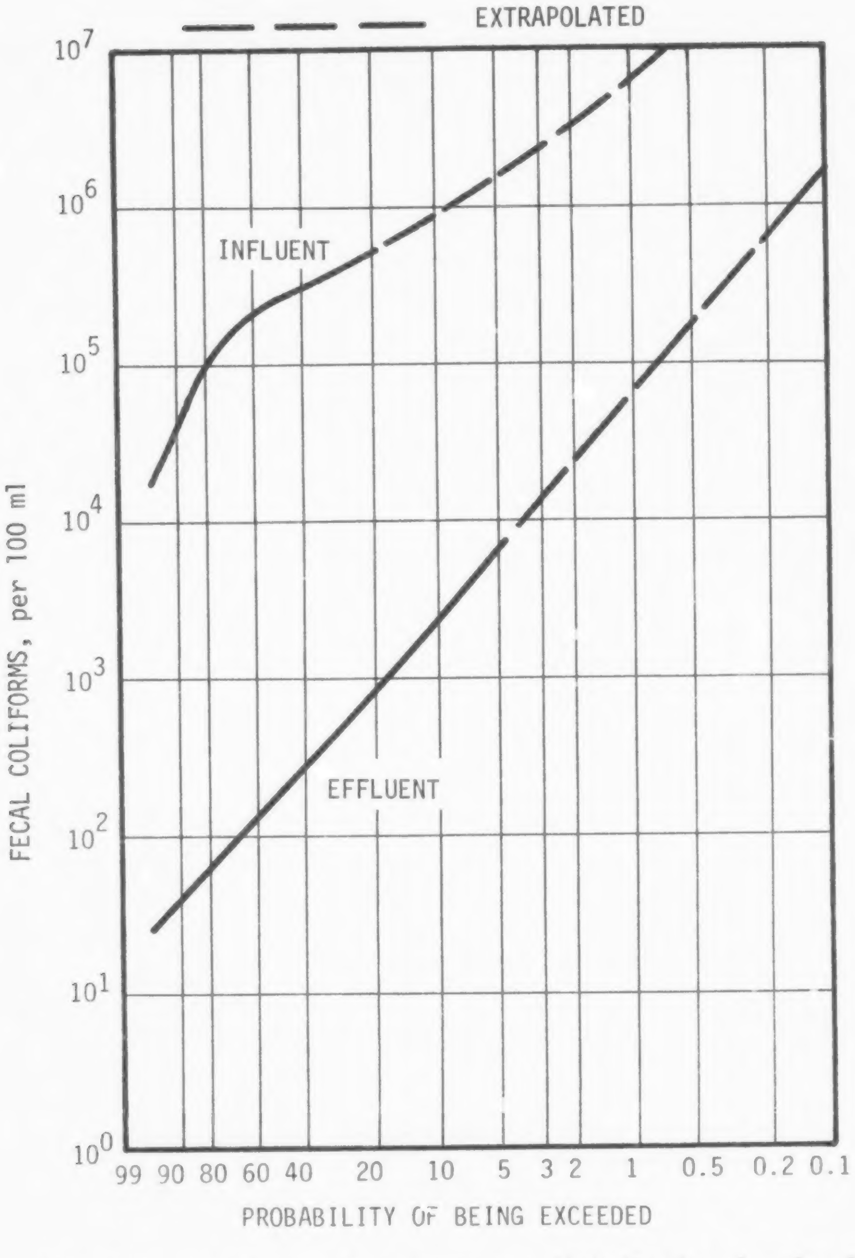


Figure 24. Extreme-value frequency distribution for fecal coliform data, Run No. K2.

RUN NO. K3

The Pilot Plant was configured as shown in Figure 25 for Run No. K3. The objective of this run was to obtain additional data on UV disinfection of a nitrified activated sludge effluent with the Kelly-Purdy Unit. The unit was operated at a depth of 2.54 cm (1 inch) and an average flow of 1.13 l/sec (17.9 gpm).

During this run the No. 1 activated sludge system performed reasonably well. An average of only 1.1 mg/l of ammonia nitrogen was present in the effluent, as can be seen in Table 11. The observed BOD_5, COD and TSS are typical for a municipal wastewater treatment facility; therefore, the observed disinfection should have been indicative of anticipated performance at other facilities.

Table 12 presents a summary of the water quality data which were obtained from analyses on the grab samples collected for microbiological examination. Turbidity values and observed total suspended solids concentrations were somewhat higher than in Run No. K2; however, color and soluble TOC concentrations were comparable.

Table 12 also summarizes the results of disinfection for Run No. K3. Figures 26, 27, and 28 present data for standard plate counts, total coliforms, and fecal coliforms, respectively. Although relatively good bacterial reductions were achieved during this run (3.1 logs for fecal coliforms), the effluent would not have met a 200 fecal coliforms per 100 ml standard.

The intensity of the UV light at the water surface was spot checked periodically during all of the Kelly-Purdy runs. These checks indicated that no change in UV intensity occurred; therefore, the previously reported mean UV intensity (at the water surface) of the 1190 μwatts/cm^2 has been used for all dose calculations. Additionally, during this portion of the project activated sludge effluent transmittance data at a wavelength of 254 nm were not available. An extinction coefficient, k, of 0.5 cm^{-1} was assumed for the purposes of calculating the average UV intensity in the water flowing through the Kelly-Purdy unit.

During this run the average flow of 1.13 liters per second resulted in an average theoretical residence time of 36 seconds. With the depth of flow set at 2.54 cm, and an assumed extinction coefficient of 0.5 cm^{-1}, the mean UV intensity in the irradiated activated sludge effluent was 674 μwatts/cm^2. The computed UV dose was 24,500 μwatt-sec/cm^2.

The observed reductions in bacterial populations were not sufficient to satisify a typical disinfection limitation of 200 fecal coliforms per 100 ml. The fecal coliform data shown in Figure 28 indicate that relatively consistent reductions were obtained during this run; however, the extreme-value frequency distribution (EVFD) in Figure 31 indicates that 38 percent of the samples exceeded 400 fecal coliforms per 100 ml. The EVFD for the total coliform data indicates that 24 percent of the samples exceeded 2000

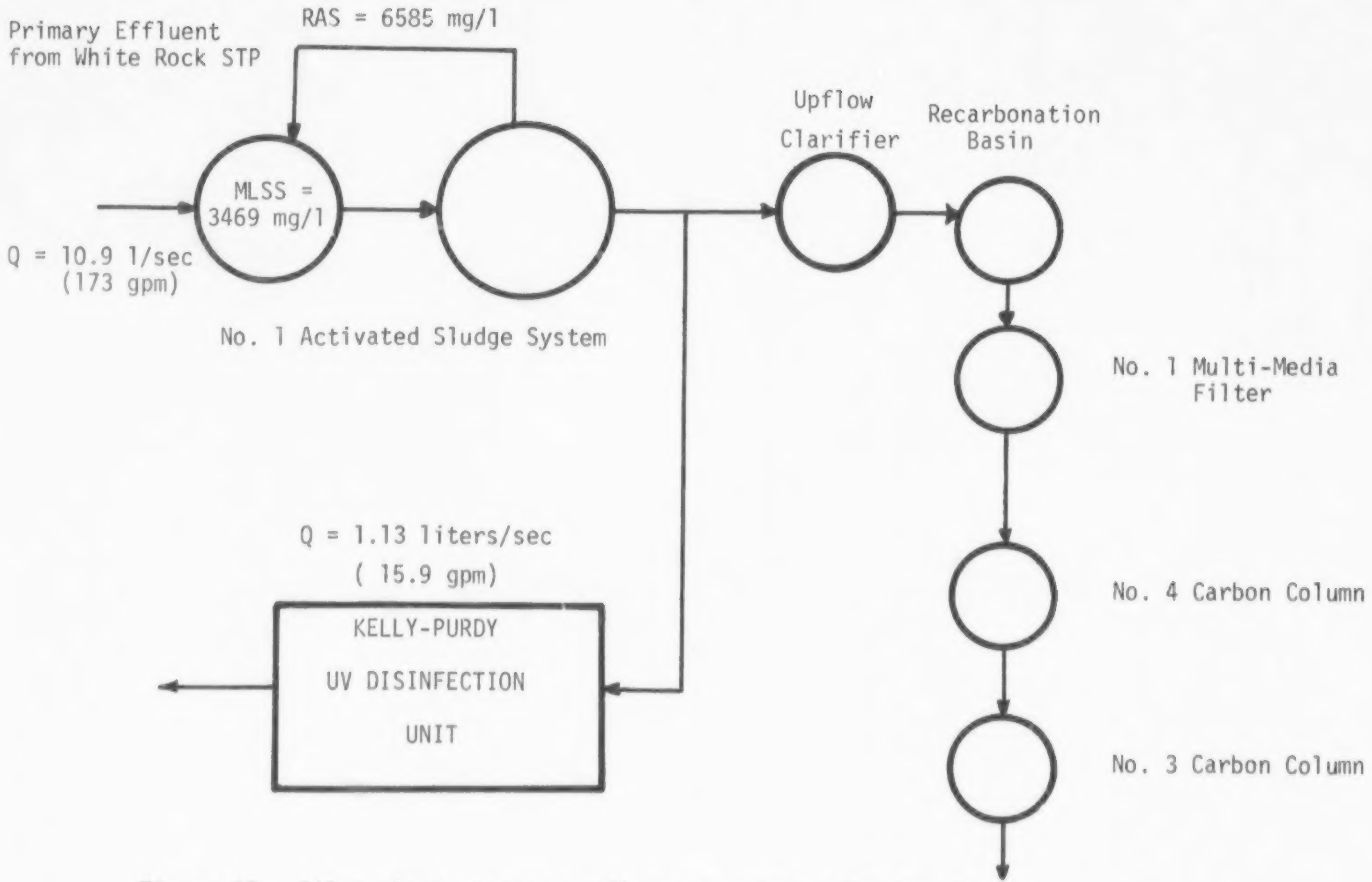

Primary Effluent
from White Rock STP
RAS = 6585 mg/1
MLSS =
3469 mg/1
Q = 10.9 1/sec
(173 gpm)
No. 1 Activated Sludge System
Upflow
Clarifier
Recarbonation
Basin
No. 1 Multi-Media
Filter
No. 4 Carbon Column
No. 3 Carbon Column
Q = 1.13 liters/sec
(15.9 gpm)
KELLY-PURDY
UV DISINFECTION
UNIT

Figure 25. Pilot plant process configuration during Run No. K3.

TABLE 11. SUMMARY OF NO. 1 ACTIVATED SLUDGE SYSTEM PERFORMANCE DURING RUN NO. K3

Parameter	Activated Sludge Influent mg/l	Activated Sludge Effluent mg/l	Reduction percent
TSS	126	27	78.6
BOD_5	161	12	92.5
COD	328	43	86.9
TOC, soluble	-	11.8	-
NH_3-N	16.6	1.1	93.4
Org. N	8.7	3.3	62.1
NO_2 & NO_3-N	0.4	7.8	-
Total N	25.7	12.2	52.5
Total P	10.8	7.7	28.7
Turbidity,NTU	-	8.4	-
Color, Pt-Co units	-	44	-

TABLE 12. RESULTS OF RUN NO. K 3

Parameter	Influent					Effluent					
	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow Rate, l/sec	15	0.76	1.26	1.13		-	-	-	-	-	-
Turbidity, NTU	24	2.5	32	8.4		24	3.0	35	8.6	-	-
TSS, mg/l	24	7	100	26		24	6	100	25	-	-
Color, Pt-Co Units	12	30	60	44		12	20	50	37	-	-
TOC mg/l	8	8	16	11		10	9	16	12	-	-
Standard Plate Count per ml	11	$2.6x10^4$	$8.7x10^5$	$1.8x10^5$	5.26	12	$1.9x10^2$	$2.5x10^3$	$7.6x.0^2$	2.88	2.38
Total Coliforms per 100 ml	12	$1.0x10^5$	$3.8x10^7$	$3.1x10^6$	6.49	12	$1.0x10^2$	$5.0x10^3$	$8.7x10^2$	2.94	3.55
Fecal Coliforms per 100 ml	12	$6.9x10^4$	$4.5x10^6$	$3.8x10^5$	5.58	11	$1.2x10^2$	$1.7x10^3$	$3.1x10^2$	2.49	3.09

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

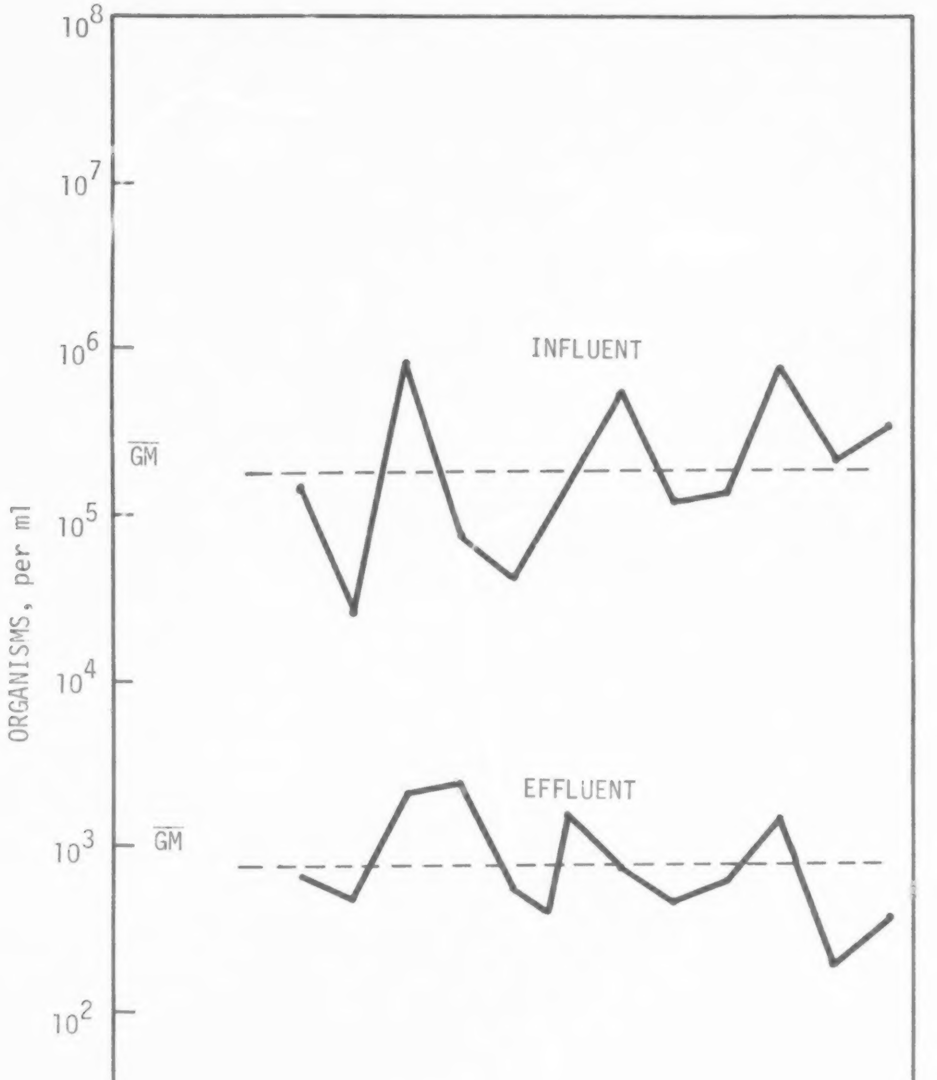


Figure 26. Standard plate count data for Run No. K3.

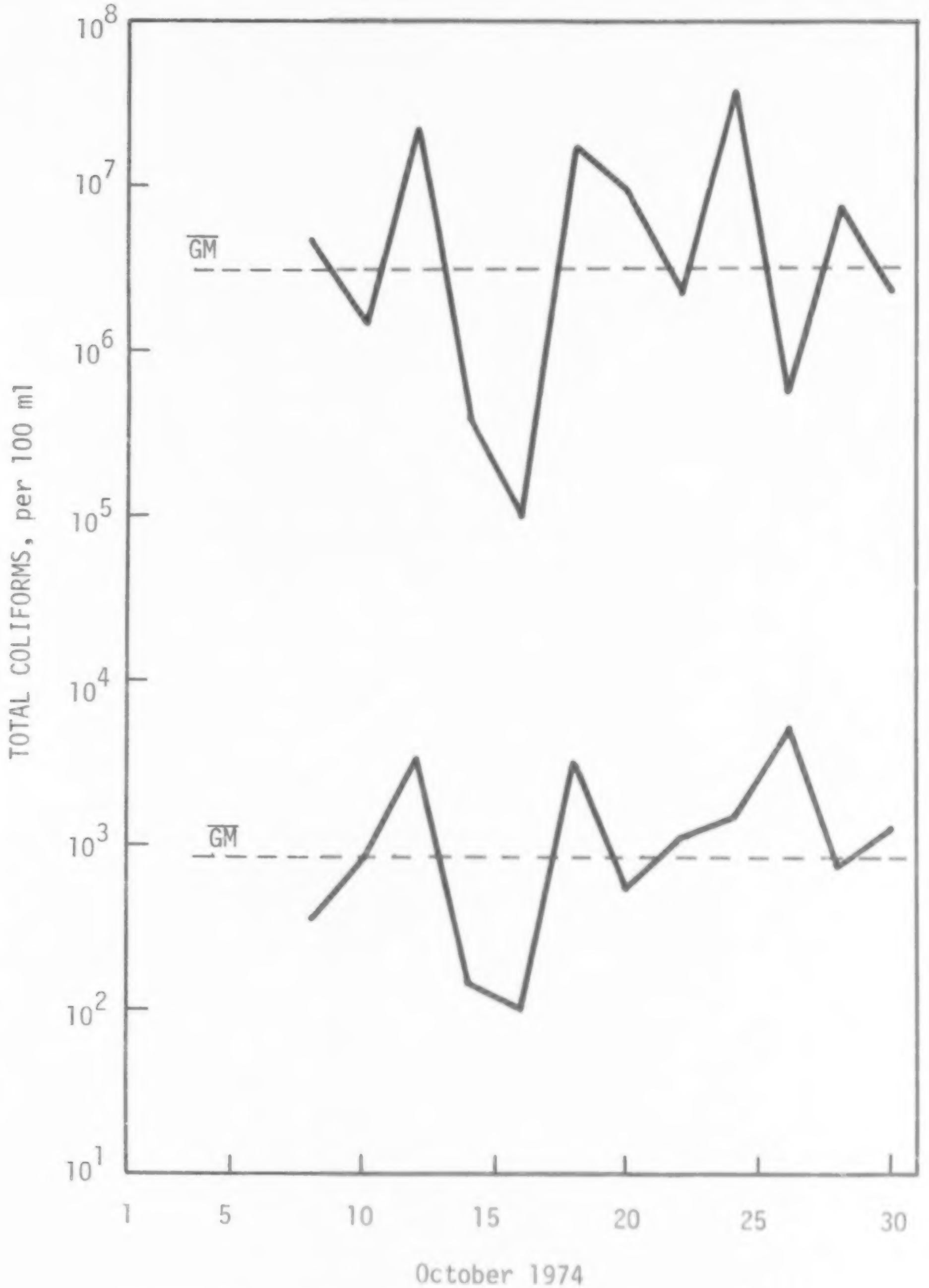


Figure 27. Total coliform data for Run No. K3.

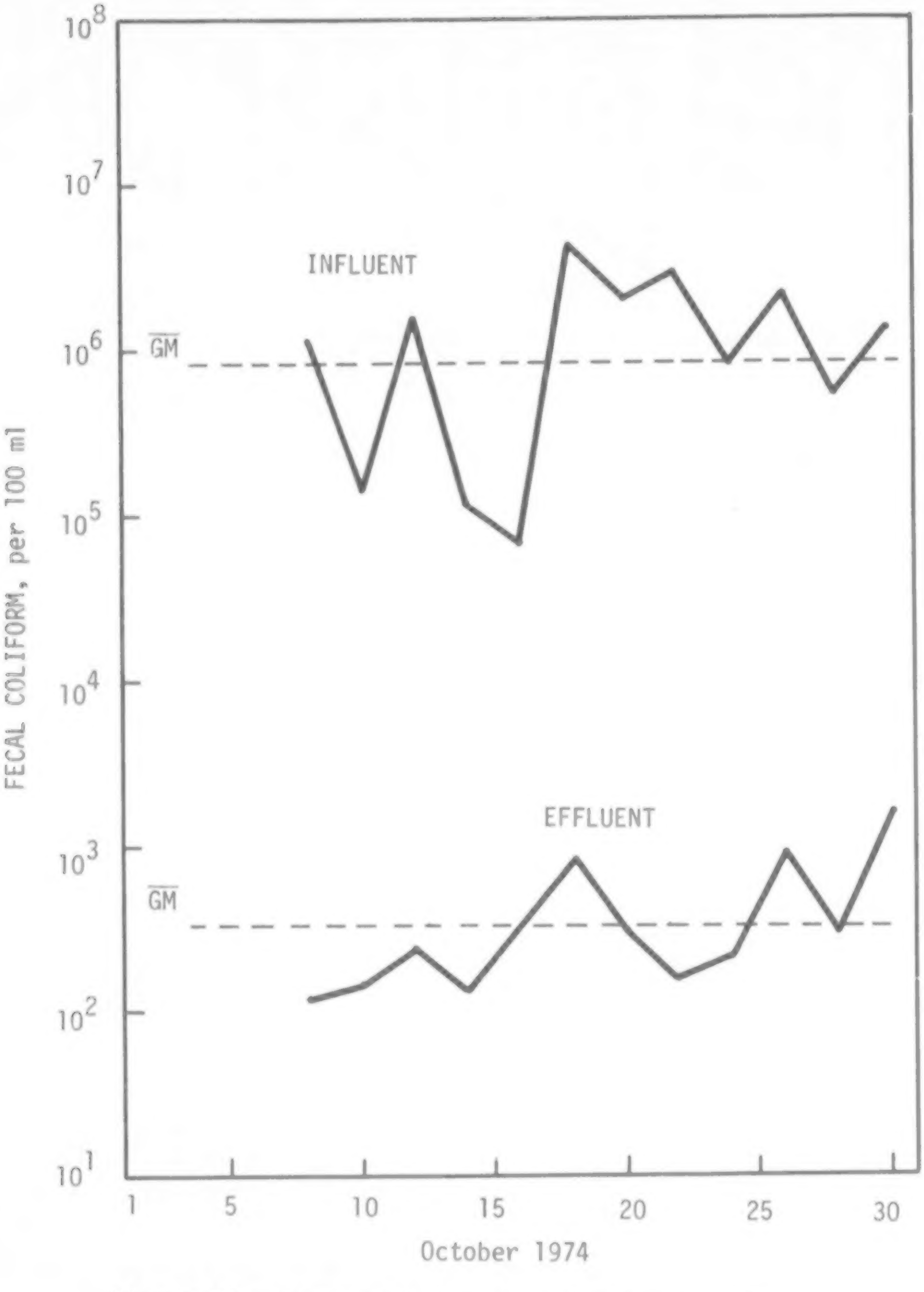


Figure 28. Fecal coliform data for Run No. K3

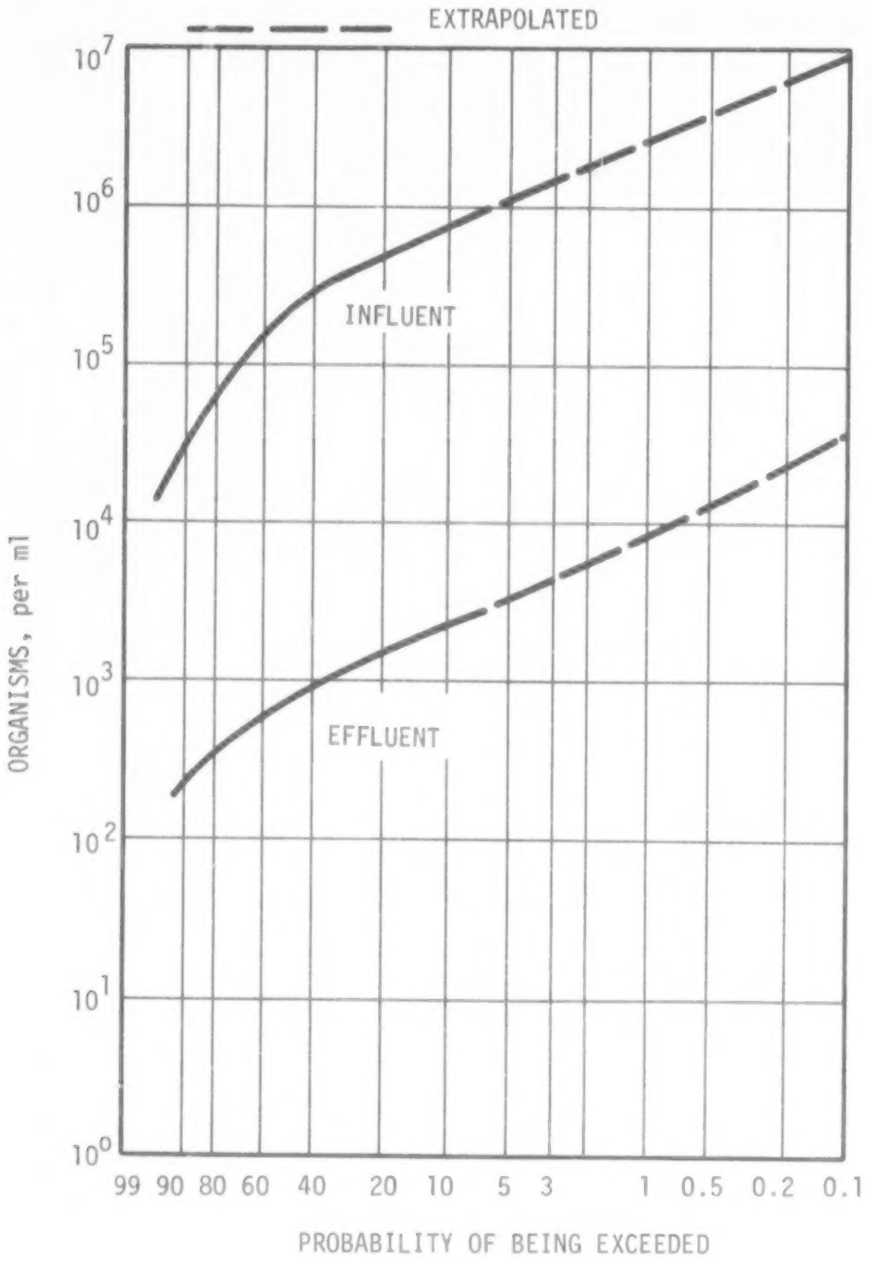


Figure 29. Extreme-value frequency distribution for standard plate count data, Run No. K3.

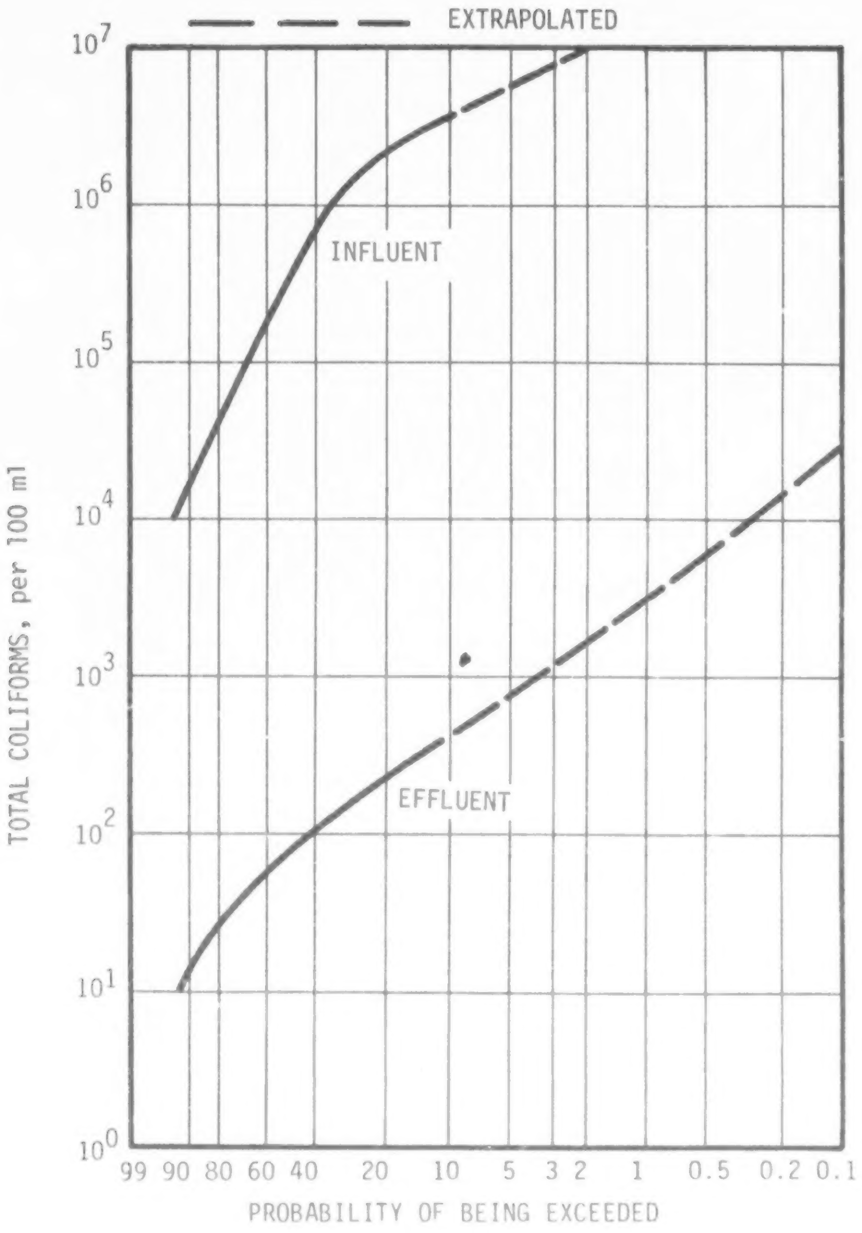


Figure 30. Extreme-value frequency distribution for total coliforms, Run No. K3.

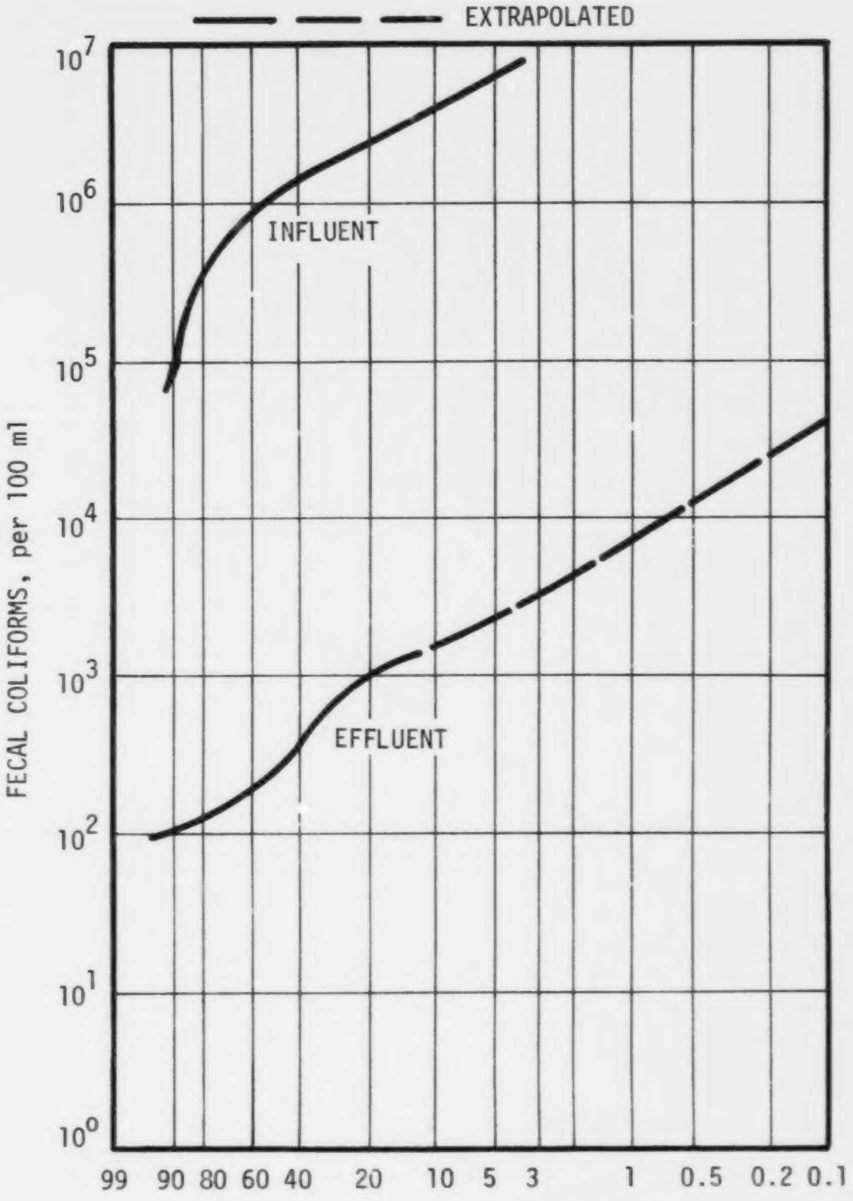


Figure 31. Extreme-value frequency distribution for fecal coliform data, Run No. K3.

coliforms per 100 ml.

Although 3.09 and 3.55 log reductions were observed for fecal coliforms and total coliforms, respectively, the effluent counts were higher than desired. The dose of 24,300 μwatt-sec/cm^2 was insufficient to provide adequate disinfection.

RUN NO. K4

Inasmuch as the previous UV disinfection runs had indicated that the Kelly-Purdy unit was not capable of adequately disinfecting a nitrified activated sludge effluent to the 200 fecal coliform per 100 ml effluent limitation, a filtered nitrified activated sludge effluent was studied. The Pilot Plant was configured such that a portion of the effluent from the No. 1 activated sludge system was pumped to the No. 2 multimedia filter (sand and anthracite). The flow then proceeded by gravity to the Kelly-Purdy unit, which was operated at a water depth of 2.54 cm. The process configuration is shown in Figure 32.

During the time Run No. K4 was being conducted, complete nitrification was achieved as indicated in Table 13, where the average ammonia nitrogen concentration was 0.2 mg/l. Overall wastewater quality during this period was excellent, as indicated by the low levels of TSS and COD in the filtered effluent.

The water quality data obtained from the grab samples collected for microbiological analyses are shown in Table 14, and are indicative of a relatively high-quality secondary effluent.

The average flow rate of the filtered, activated sludge effluent to the Kelly-Purdy unit was 0.96 liters per second. At the operating depth of 2.54 cm, the 0.96 liters per second flow resulted in a theoretical residence time of 43 seconds. In the absence of transmissability data, an assumed extinction coefficient of 0.4 cm^{-1} was used to compute an average UV intensity in the water of 747 μwatts/cm^2. The lower value for k was selected due to improved effluent quality, when compared to the unfiltered activated sludge effluent. This combination of residence time (43 seconds) and UV intensity results in a theoretical UV dose of 32,000 μwatt-sec/cm^2.

The observed log reductions reported in Table 14 were only slightly higher than the reductions observed in previous runs, and the influent counts of all three microbiological water quality indicators were about one log lower than in Runs K3 and K1. Both of these factors partially explain the reason the fecal coliform data complied with the 200 F.C./100 ml standard.

Time-series plots of the microbiological data are shown in Figures 33 through 35. All three graphs indicate that the respective influent population densities were reasonably constant, but the effluent counts are significantly lower during the middle of November. The examination of all available water quality data failed to identify any reason for the mid-month

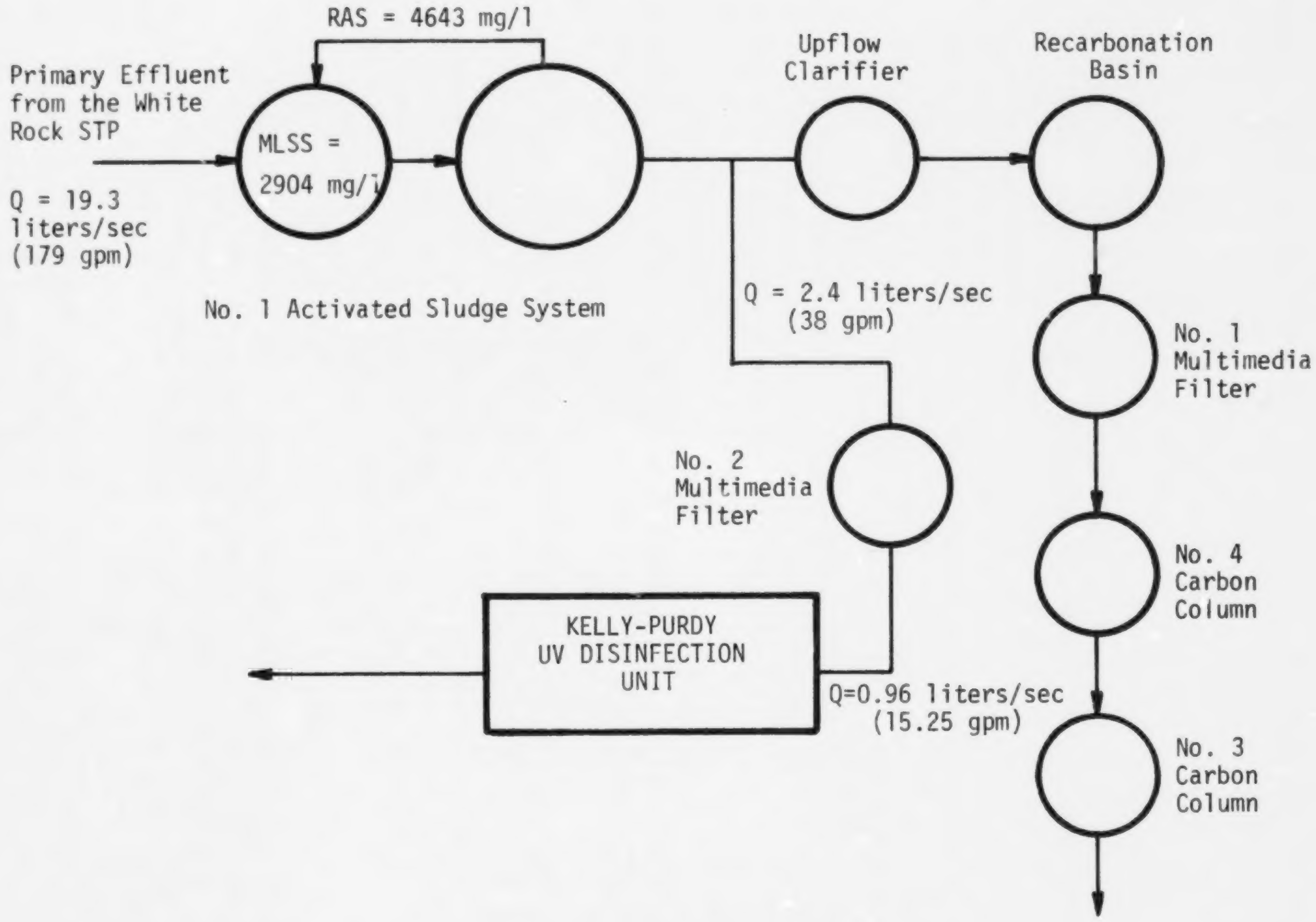

RAS = 4643 mg/1
Primary Effluent from the White Rock STP
Q = 19.3 liters/sec (179 gpm)
MLSS = 2904 mg/l
No. 1 Activated Sludge System
Upflow Clarifier
Recarbonation Basin
Q = 2.4 liters/sec (38 gpm)
No. 1 Multimedia Filter
No. 2 Multimedia Filter
No. 4 Carbon Column
KELLY-PURDY UV DISINFECTION UNIT
Q=0.96 liters/sec (15.25 gpm)
No. 3 Carbon Column

Figure 32. Pilot Plant process configuration during Run No. K4.

TABLE 13. PERFORMANCE OF NO. 1 ACTIVATED SLUDGE SYSTEM AND NO. 2 MULTIMEDIA FILTER DURING RUN NO. K4

Parameter	A. S. Inf. mg/l	A. S. Eff. mg/l	No.2 Filter Effluent mg/l	Reduction percent
TSS	146	15	5	96.6
COD	287	31	20	93.0
TOC, soluble	-	9.5	9.7	-
NH_3-N	11.6	0.2	0.2	98.3
Org. N	9.1	2.4	1.8	80.2
NO_2 & NO_3-N	0.3	8.5	8.7	-
Total N	21.0	11.1	10.7	49.0
Total P	6.4	4.2	4.3	32.8
Turbidity, NTU	-	2.6	2.5	3.8
Color, Pt-Co units	-	25	31	-

TABLE 14. RESULTS OF RUN NO. K 4

Parameter	Influent					Effluent					
	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean	Log of Mean[2]	Mean Log Reduction[2]
Flow, 1/sec	26	0.8	1.7	0.96	-	-	-	-	-	-	-
Turbidity, NTU	22	0.7	7.5	2.6	-	22	0.8	6.3	2.5	-	-
TSS, mg/1	22	2	21	6.7	-	22	2	67	9.2	-	-
Color, Pt-Co Units	18	10	30	25	-	18	10	45	31	-	-
TOC, mg/1	12	5	15	9	-	12	6	16	10	-	-
COD, mg/1	2	14	14	14	-	-	-	-	-	-	-
Standard Plate Count per ml.	18	4.8×10^4	5.0×10^5	7.7×10^4	4.89	18	1.6×10^1	3.3×10^2	8.7×10^1	1.94	2.95
Total Coliform per 100 ml	21	2.6×10^5	2.8×10^6	5.8×10^5	5.76	20	1.1×10^0	4.1×10^3	8.5×10^1	1.93	3.83
Fecal Coliform per 100 ml	20	1.0×10^3	2.7×10^5	5.2×10^4	4.72	21	$<1.0\times10^0$	1.0×10^2	$<2.1\times10^1$	<1.32	>3.40

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

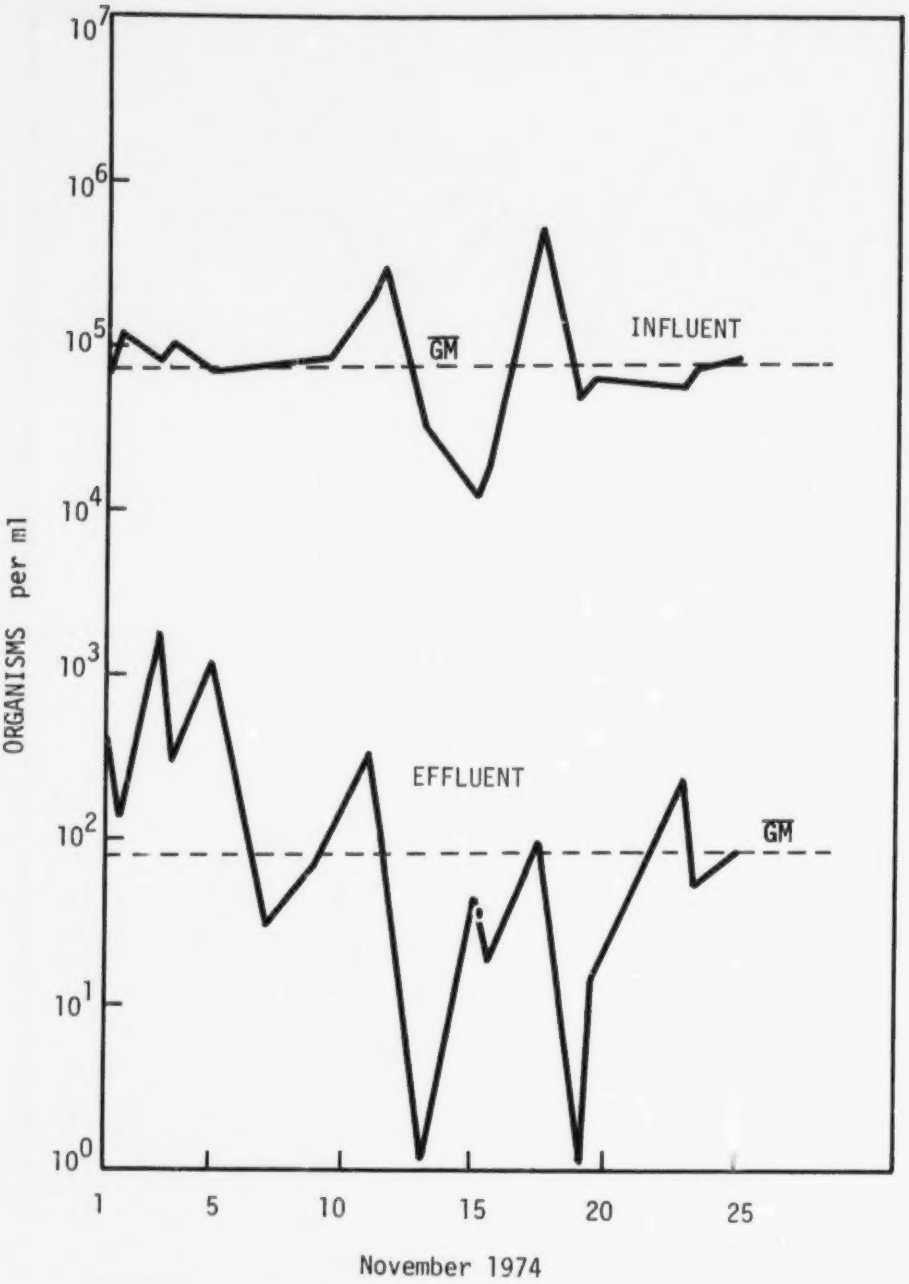


Figure 33. Standard plate count data for Run No. K4.

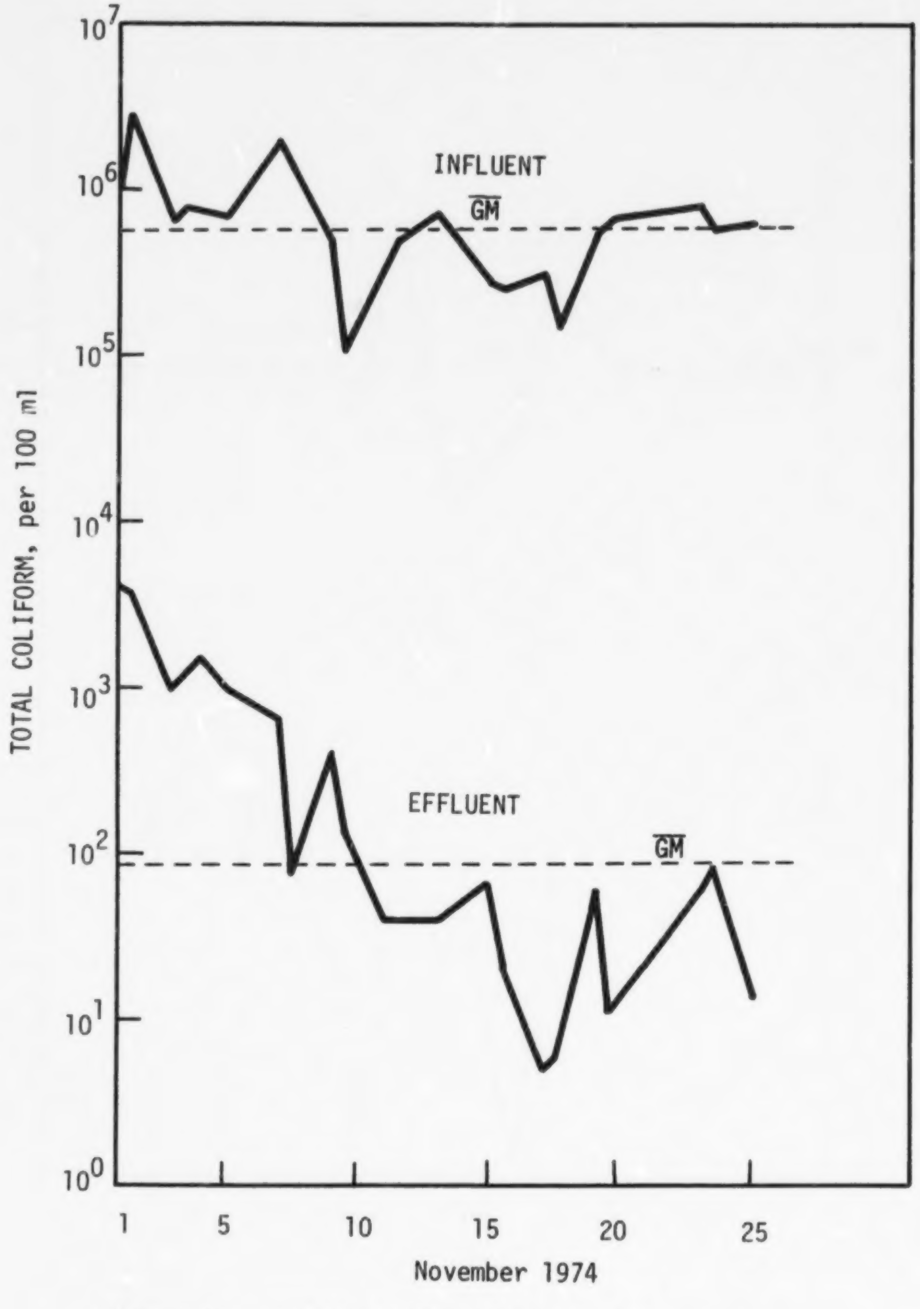


Figure 34. Total coliform data for Run No. K4.

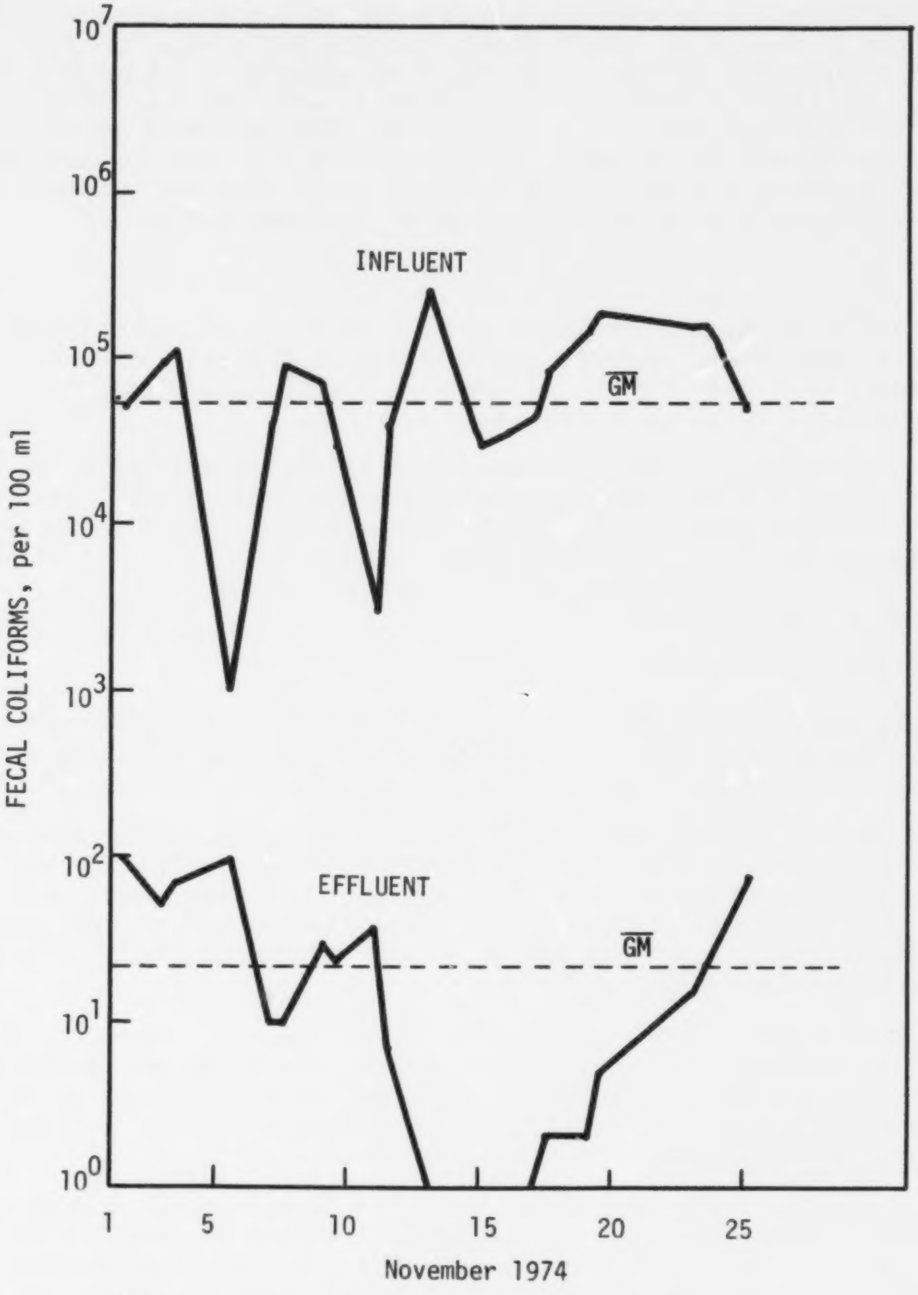


Figure 35. Fecal coliform data for Run No. K4.

decrease.

The EVFD's for the microbiological water quality data are presented in Figures 36 through 38. These curves indicate that a fecal coliform density greater than 200 per 100 ml should be expected in 2.5 percent of the samples, and that 0.6 percent of the samples exceeded 400 F.C./100 ml. The EVFD's indicate that even with a high quality effluent, which can be disinfected to meet the effluent limitation of 200 F.C./100 ml (based on a geometric mean), a significant probability exists that the treatment plant will fail to comply with the 400 F.C./100 ml. effluent limitation.

RUN NO. K5

The Pilot Plant was configured as shown in Figure 39 during Run No. K5. The Kelly-Purdy UV Disinfection Unit was operated at a water depth of 2.54 cm (1 inch) and a mean flow of 1.4 l/sec (22.2 gpm). The effluent from the No. 1 activated sludge system was used in this run.

The performance of the activated sludge process during Run K5 is summarized in Table 15. The biological process suffered a substantial upset in early December when a plant operator inadvertantly left the waste sludge valve open over-night. The result was a reduction in MLSS from about 3500 mg/l to 250 mg/l, and almost a complete breakdown in the capability of the activated sludge process to treat wastewater. During this time effluent quality deteriorated significantly and the remainder of the month was spent recovering from the process upset.

Data obtained from the analyses of grab samples collected for microbiological examination are presented in Table 16. Color and turbidity were substantially higher than in previous runs, as were TSS, COD, and TOC.

Figures 40, 41, and 42 present time-series plots of the standard plate count, total coliform, and fecal coliform data, respectively. During Run No. K5 the effluent counts for the microbiological parameters were higher than the values observed during the previous runs. The coliform log reductions obtained during Run No. K5 were not substantially different than those obtained during earlier runs.

The theoretical residence time during this run was 29 seconds. If an extinction coefficient of 0.55 cm^{-1} is assumed, due to the poor effluent quality, the average UV intensity in the water can be calculated to be 641 $\mu watt/cm^2$. This combination of residence time and intensity resulted in a theoretical UV dose of only 18,800 $\mu watt\text{-}sec/cm^2$.

Examination of the time-series plots of the microbiological data indicated an apparent decrease in population densities for both the activated sludge effluent and the disinfected effluent as the biological process recovered. The fecal coliform data presented in Figure 42 indicate an almost constant three-log reduction regardless of the influent population density.

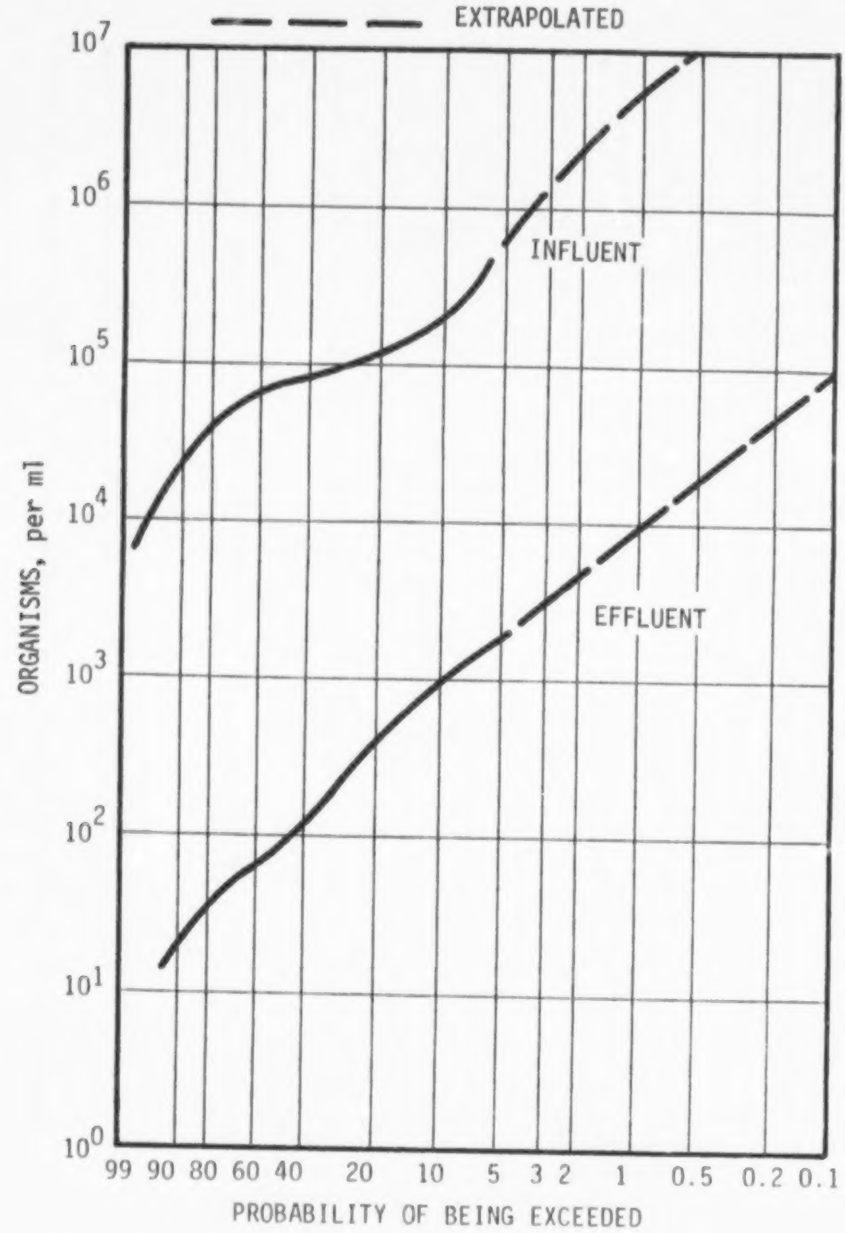


Figure 36. Extreme-value frequency distribution for standard plate count data, Run No. K4.

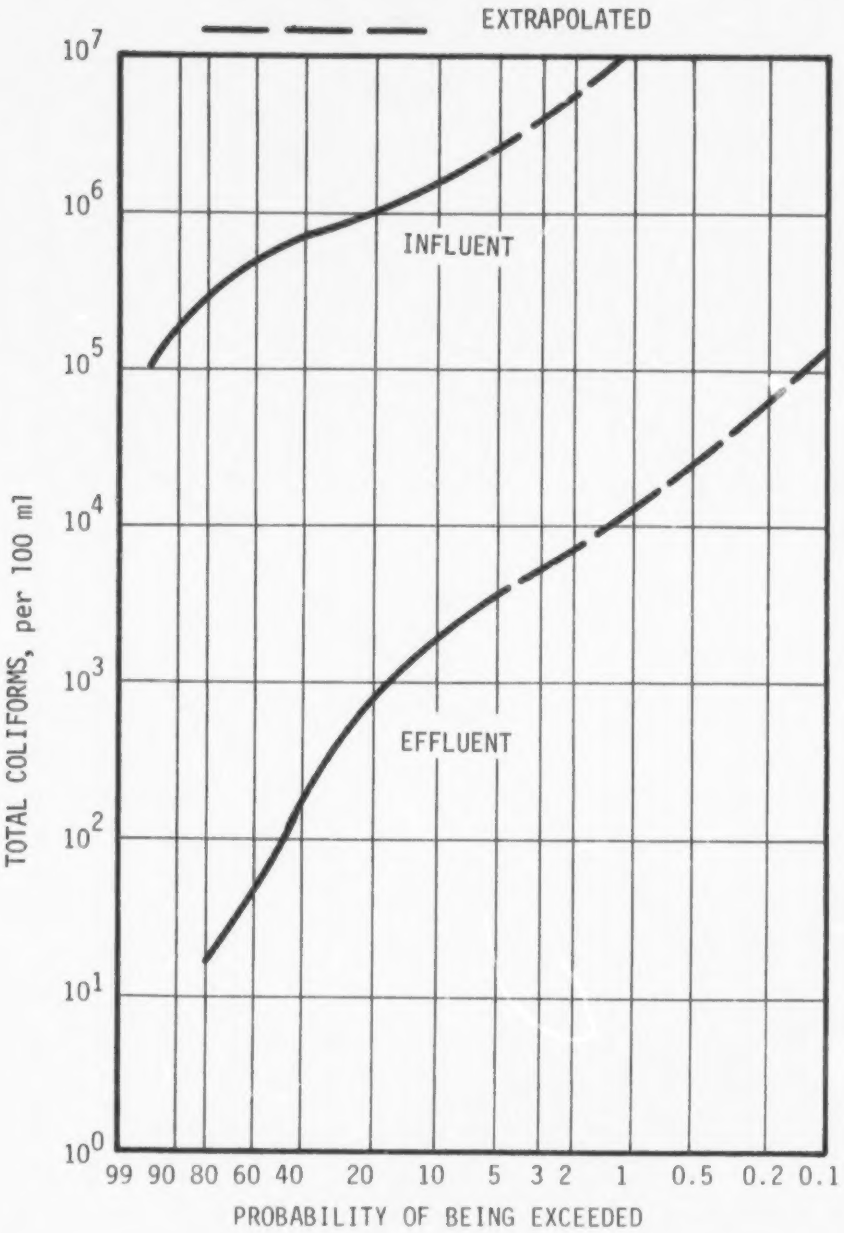


Figure 37. Extreme-value frequency distribution for total coliform data, Run No. K4.

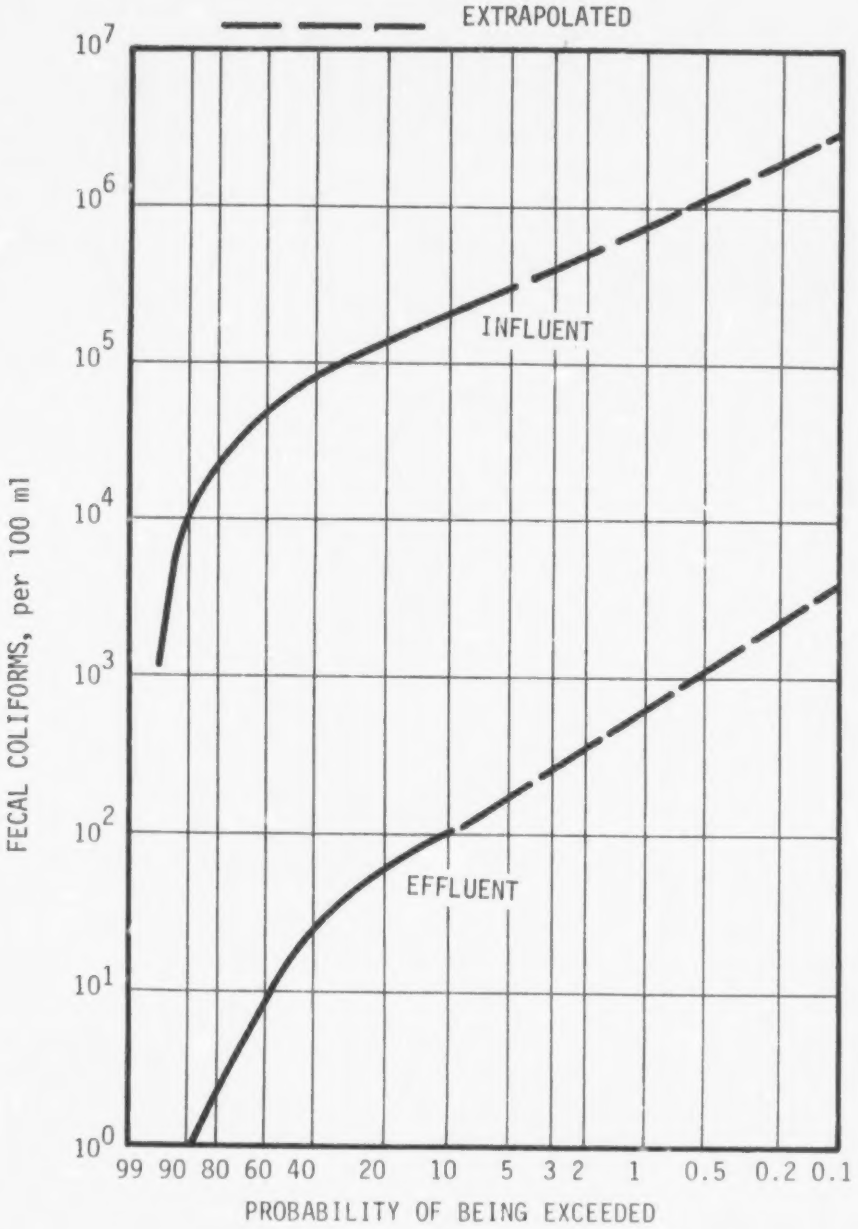


Figure 38. Extreme-value frequency distribution for fecal coliform data, Run No. K4.

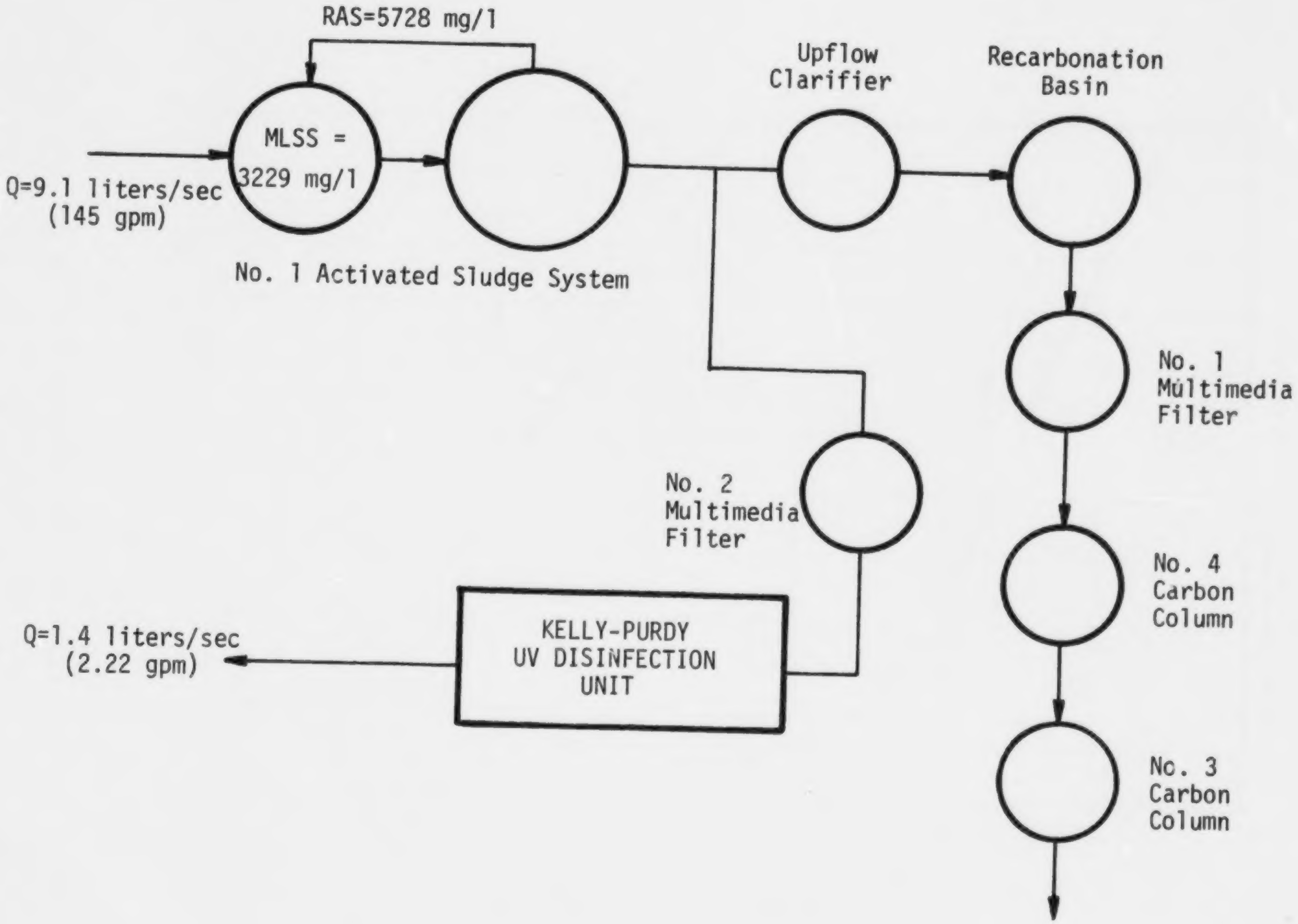

RAS=5728 mg/1
MLSS =
3229 mg/1
Q=9.1 liters/sec
(145 gpm)
No. 1 Activated Sludge System
Upflow
Clarifier
Recarbonation
Basin
No. 1
Multimedia
Filter
No. 4
Carbon
Column
No. 3
Carbon
Column
No. 2
Multimedia
Filter
KELLY-PURDY
UV DISINFECTION
UNIT
Q=1.4 liters/sec
(2.22 gpm)

Figure 39. Pilot Plant configuration during Run No. K5.

TABLE 15. PERFORMANCE OF THE NO. 1 ACTIVATED SLUDGE SYSTEM DURING RUN NO. K5

Parameter	Activated Sludge Influent mg/l	Activated Sludge Effluent mg/l	Reduction percent
TSS	98	39	60.2
COD	217	68	68.7
TOC, soluble	-	14	-
NH_3-N	13.9	10.1	27.3
Org. N	7.6	3.6	52.6
NO_2 & NO_3-N	0.3	2.0	-
Total N	21.8	15.7	28.0
Total P	7.5	3.8	49.3
Turbidity, NTU	-	10.2	-
Color, Pt-Co units	-	>70	-

TABLE 16. RESULTS OF RUN NO. K5

Parameter	Influent					Effluent					
	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow 1/sec	13	1.01	1.64	1.40	-	-	-	-	-	-	-
Turbidity, NTU	18	4.3	22	11	-	20	8	16	12	-	-
TSS, mg/1	18	25	224	59	-	20	20	228	57	-	-
COD, mg/1	6	46	150	92	-	5	54	120	88	-	-
TOC, mg/1	16	9	45	32	-	16	9	43	31	-	-
Soluble TOC, mg/1	13	11	19	16	-	13	11	17	15	-	-
Color, Pt-Co Units	29	50	>70	>70	-	29	55	>70	>70	-	-
Standard Plate Count per ml	10	$1.3\text{x}10^5$	$1.4\text{x}10^7$	$2.3\text{x}10^6$	6.36	9	$6.4\text{x}10^3$	$6.4\text{x}10^3$	$1.9\text{x}10^5$	4.48	1.88
Total Coliforms per 100 ml	13	$1.1\text{x}10^6$	$5.0\text{x}10^7$	$8.4\text{x}10^6$	6.92	11	$6.3\text{x}10^3$	$5.4\text{x}10^5$	$5.6\text{x}10^4$	4.75	2.17
Fecal Coliforms per 100 ml	12	$1.0\text{x}10^5$	$1.8\text{x}10^7$	$1.6\text{x}10^6$	6.20	11	$1.0\text{x}10^2$	$3.3\text{x}10^4$	$1.6\text{x}10^3$	3.20	3.00

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

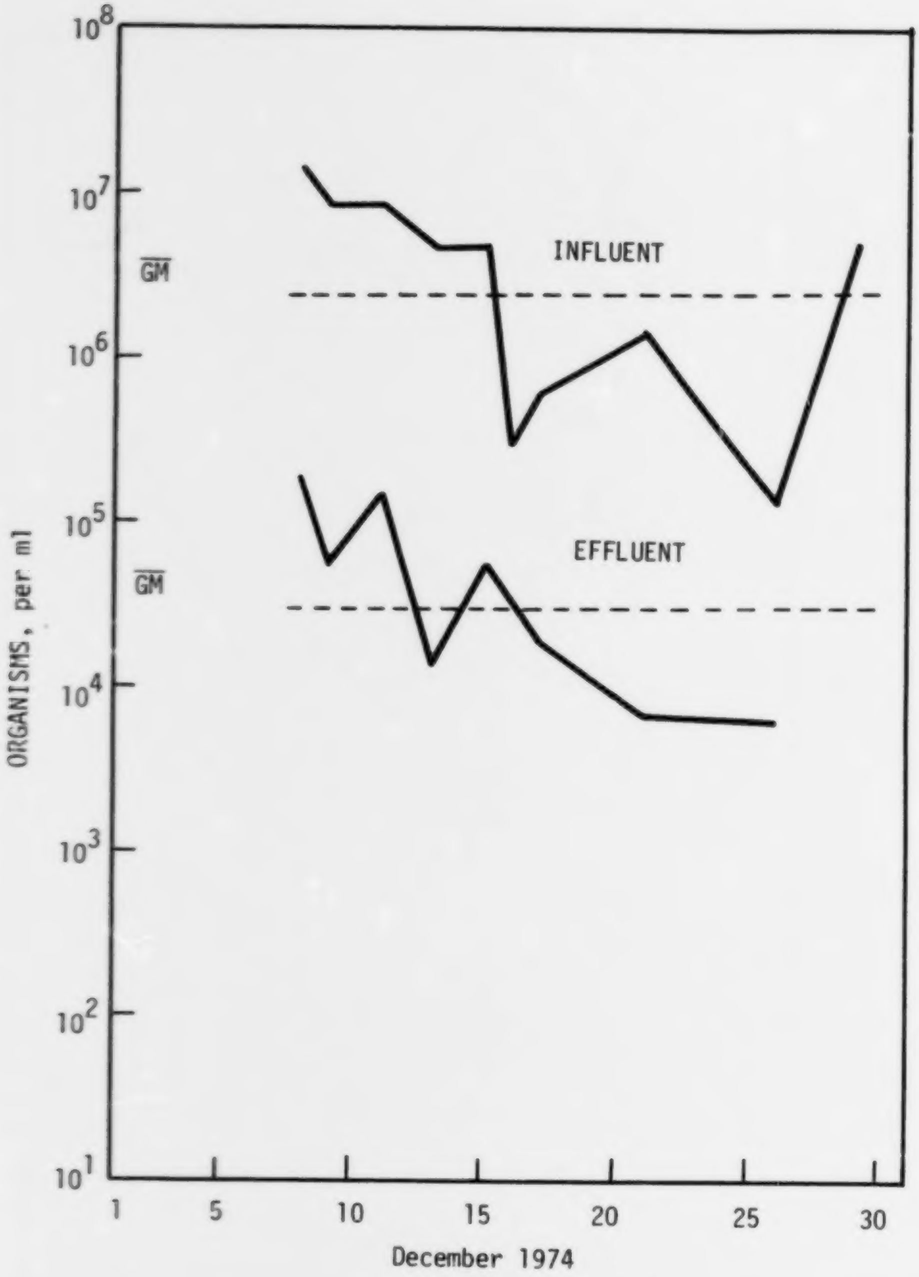


Figure 40. Standard plate count data for Run No. K5

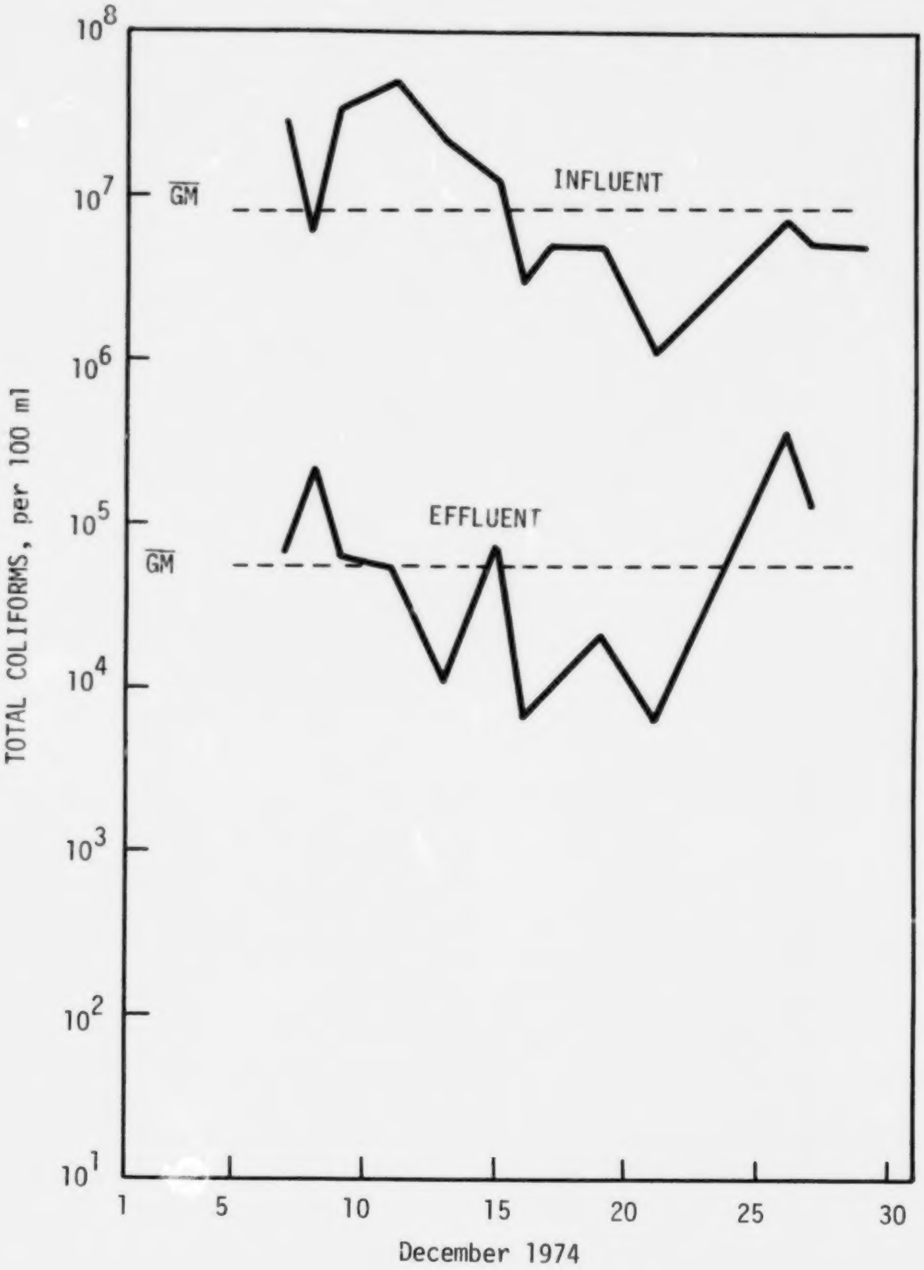


Figure 41. Total coliform data for Run No. K5.

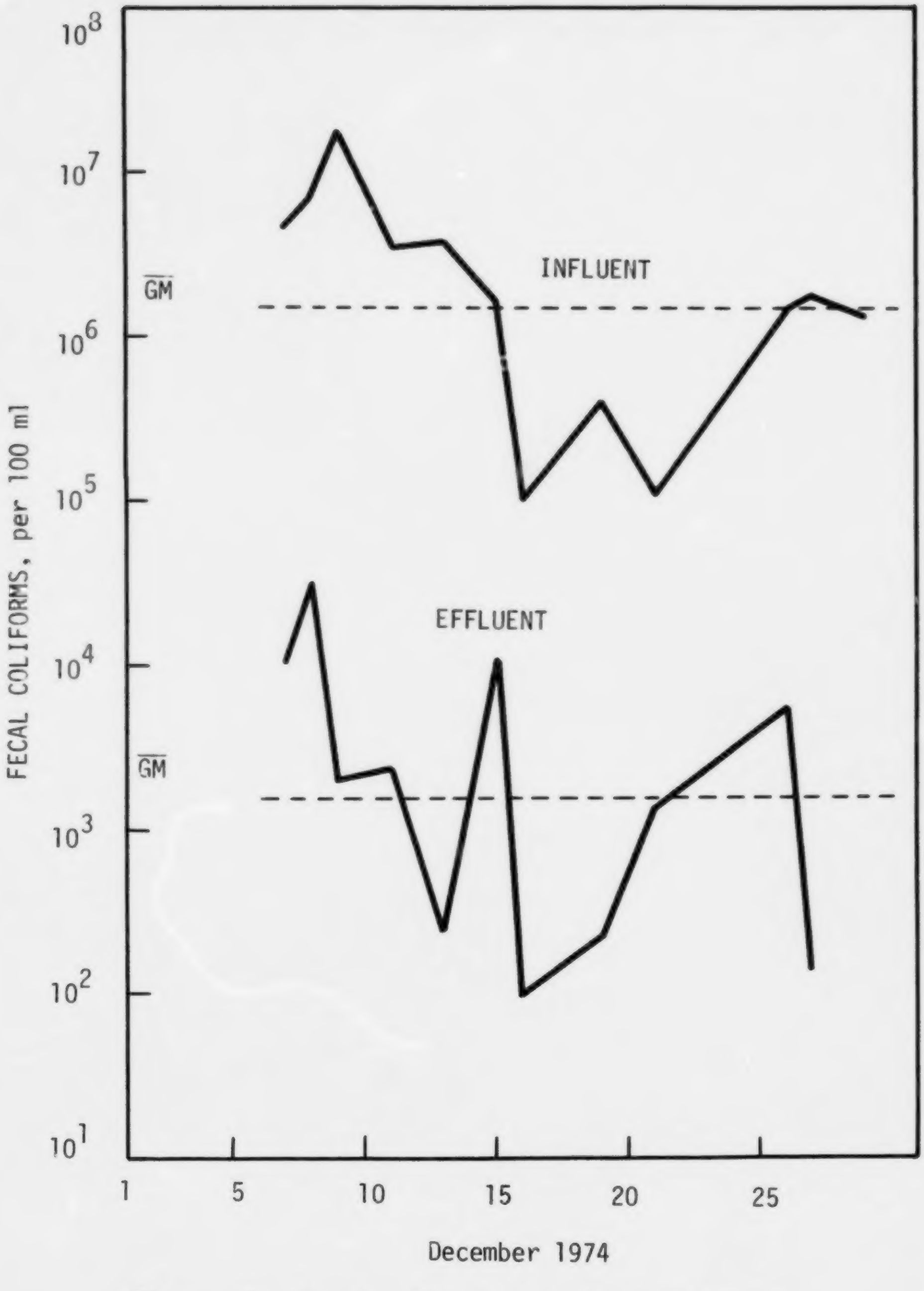


Figure 42. Fecal coliform data for Run No. K5.

The EVFD's presented in Figures 43 through 45 indicate that process performance was much less consistent during Run No. K5 than during Run No. K4. During Run No. K5, 80 percent of the UV disinfected samples exceeded 200 F.C./100 ml, and 72 percent exceeded 400 F.C./100 ml.

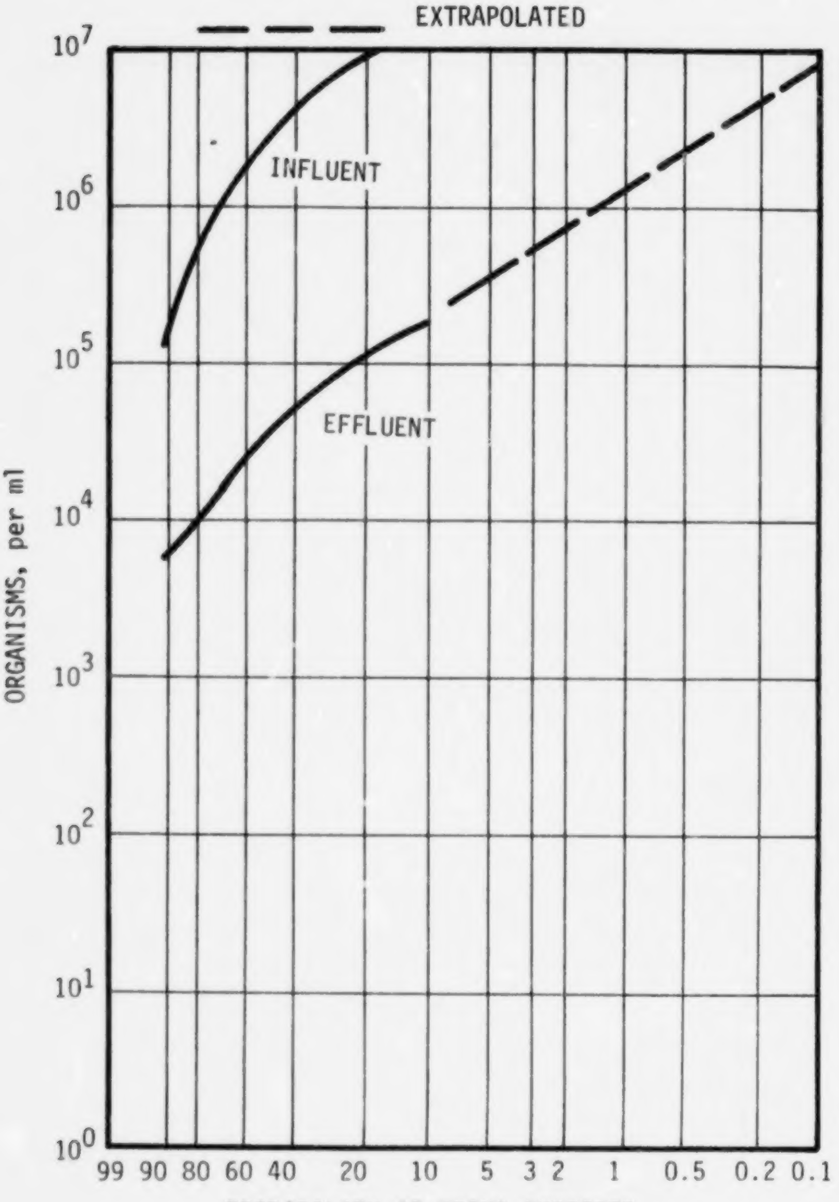


Figure 43. Extreme-value frequency distribution for standard plate count data, Run No. K5.

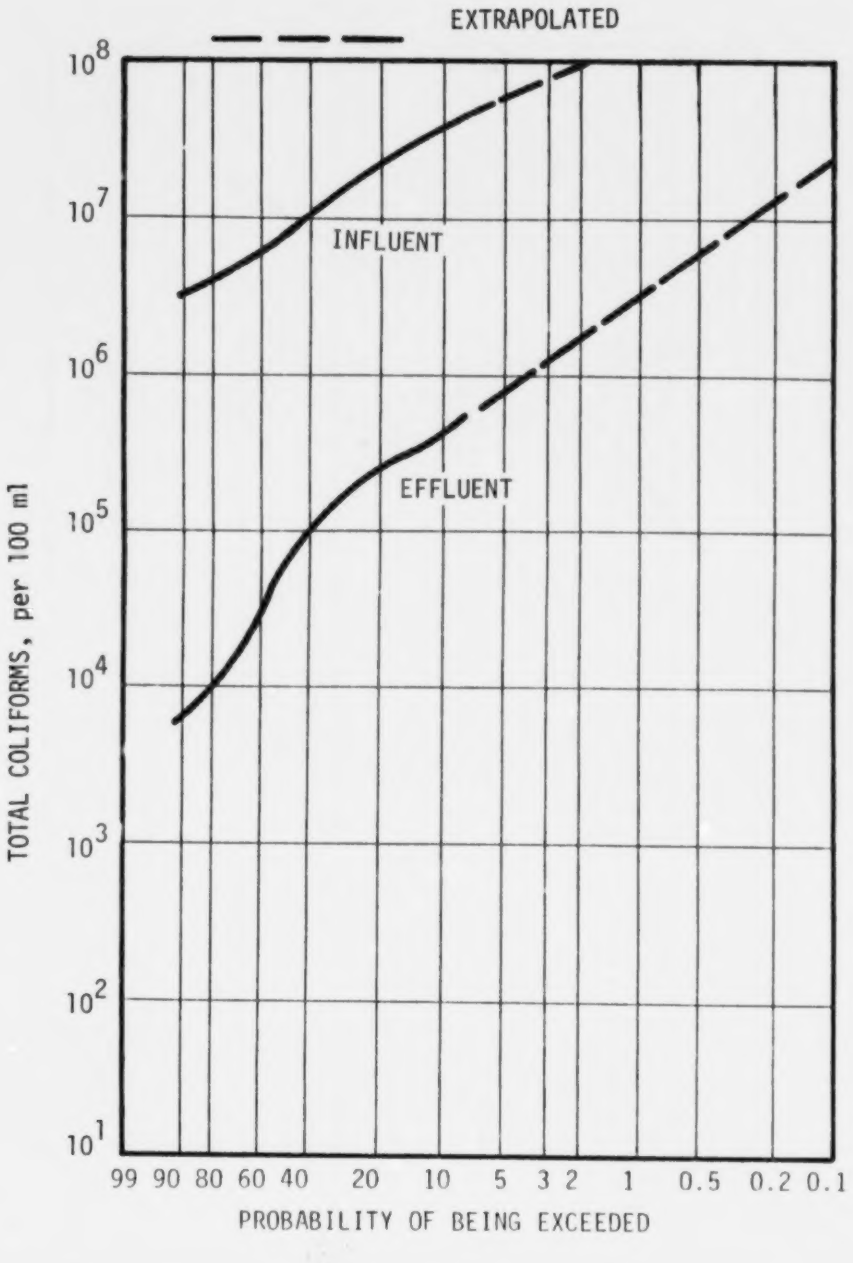


Figure 44. Extreme-value frequency distribution for total coliform data, Run No. K5.

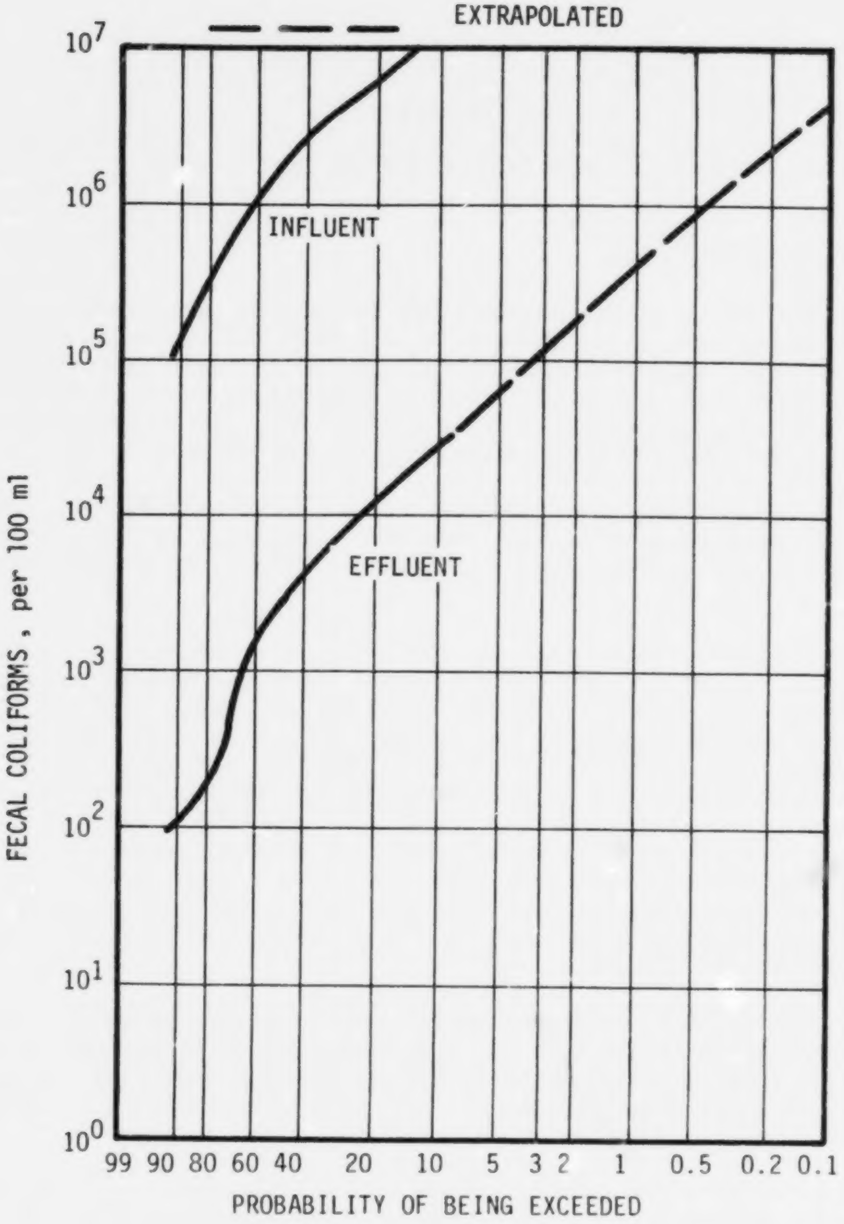


Figure 45. Extreme-value frequency distribution for fecal coliform data, Run No. K5.

SECTION 7

OPERATION OF THE UPS UNIT

HYDRAULIC CHARACTERISTICS

The model EP-50 UV disinfection system, manufactured by Ultraviolet Purification Systems, Inc., arrived in late 1974 and was brought on-line in January 1975. When the plumbing for the UPS unit was completed, the entire UV light system schematic flow diagram was as shown in Figure 46. The final study system was capable of testing any of twelve different wastewaters in either or both of the UV disinfection units.

The conceptual design of the UPS unit differed significantly from the Kelly-Purdy unit, in that the UV lamps were surrounded by the process flow instead of being suspended above a relatively thin layer of the wastewater effluent.

Theoretical residence time for the UPS unit is shown as a function of flow rate in Figure 47. Several dye tests were performed with the UPS unit so that the RTDF's for the unit could be evaluated. The resulting RTDF's are shown in Figures 48 through 50. Figure 48 presents the two RTDF's obtained at a flow rate of 0.63 liters/sec. (10 gpm). The theoretical residence time at this flow was 1.49 minutes, and the average residence time obtained from the centroids of the RTDF's was 1.83 minutes. These data indicate that the actual residence time was about 24 seconds longer than the theoretical residence time. The pronounced tailing in the RTDF's that was observed during these dye studies shifted the centroids to the right. The net effect was to significantly increase the apparent residence time.

The RTDF obtained at 1.89 liters/sec. (30 gpm) is shown in Figure 49. The theoretical residence time is 29.8 second and an actual residence time of 22 seconds was observed for this dye study. For this flow the actual residence time was eight seconds (27 percent) shorter than the theoretical residence time.

The two RTDF's obtained at a flow of 3.47 liter/sec. (55 gpm) are shown in Figure 50. The actual residence time determined from the centroids of the dye studies was 13.1 seconds, which is 3.2 seconds (20 percent) shorter than the theoretical residence time of 16.3 seconds.

Cummulative, dimensionless RTDF's for the UPS unit are shown in Figure 51. The lower flows exhibited more tailing, which is particularly

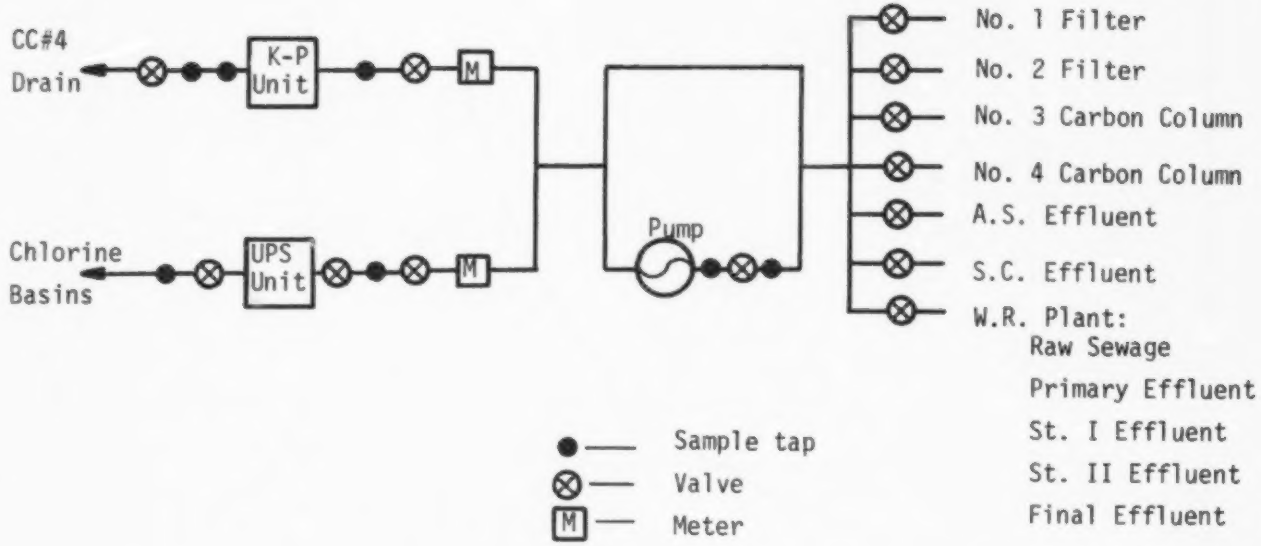

CC#4
Drain
K-P Unit
M
Chlorine
Basins
UPS Unit
M
Pump
No. 1 Filter
No. 2 Filter
No. 3 Carbon Column
No. 4 Carbon Column
A.S. Effluent
S.C. Effluent
W.R. Plant:
Raw Sewage
Primary Effluent
St. I Effluent
St. II Effluent
Final Effluent
● — Sample tap
⊗ — Valve
M — Meter

Figure 46. Schematic flow diagram of UV light system.

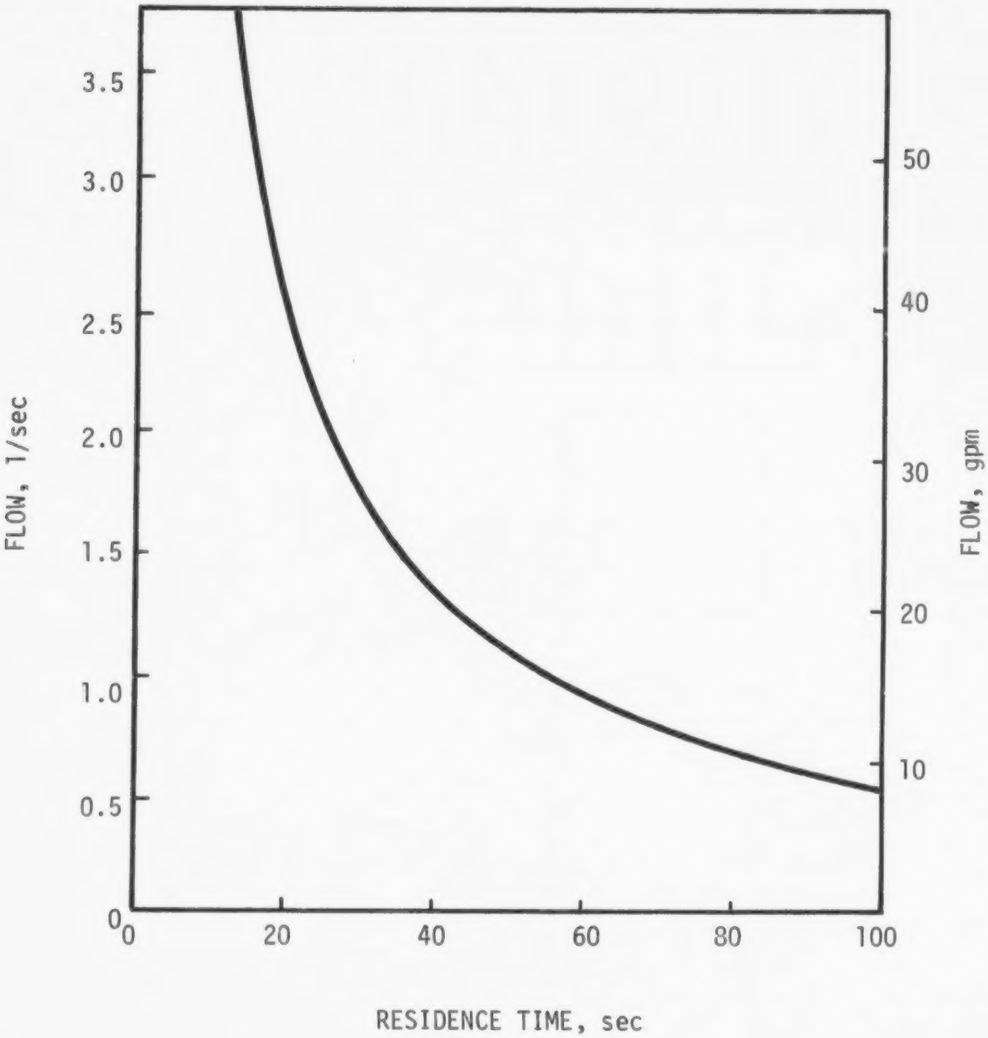


Figure 47. Theoretical residence time of UPS UV disinfection unit as a function of liquid flow rate.

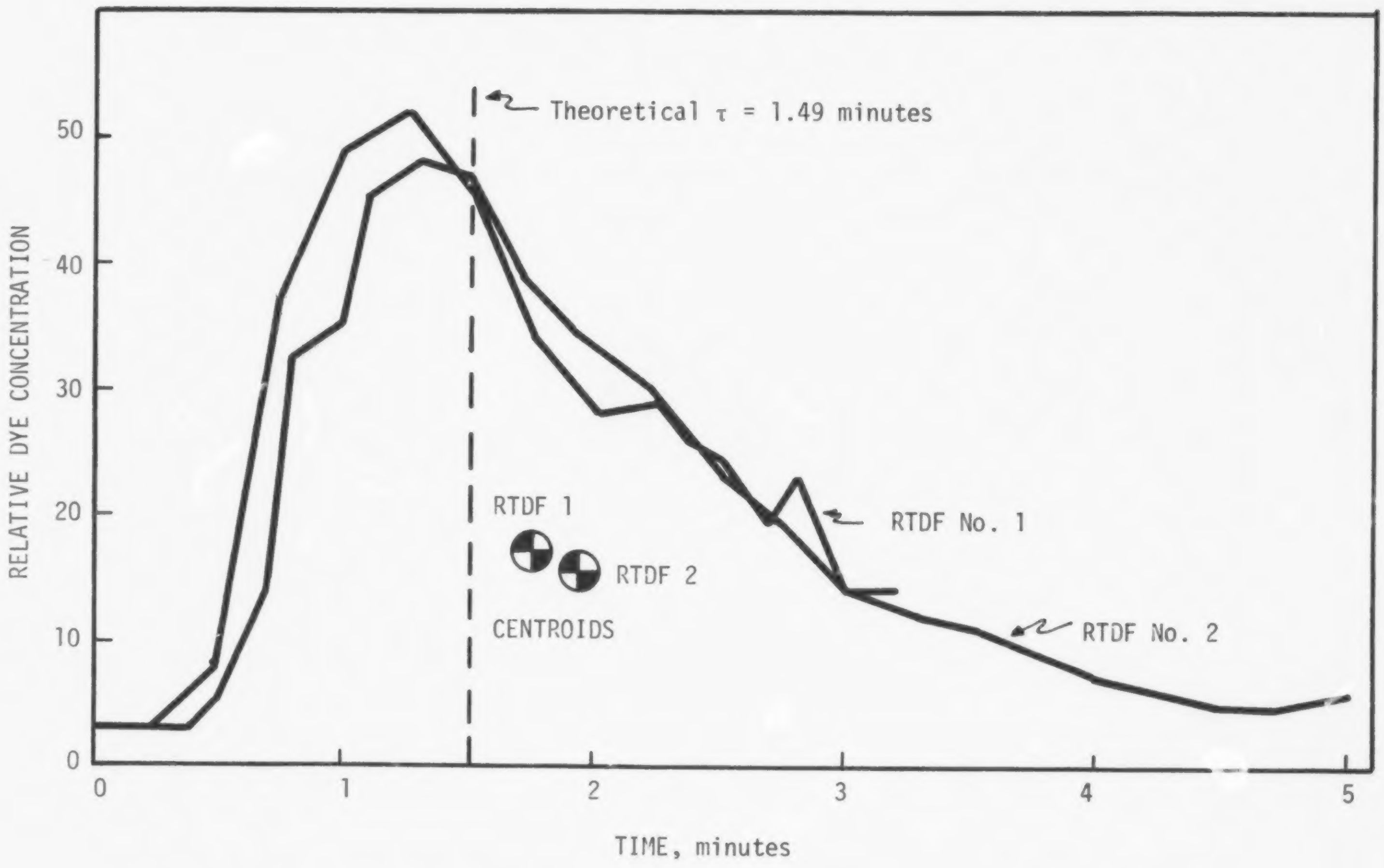


Figure 48. RTDF's for the UPS UV unit at 0.63 liters/sec.

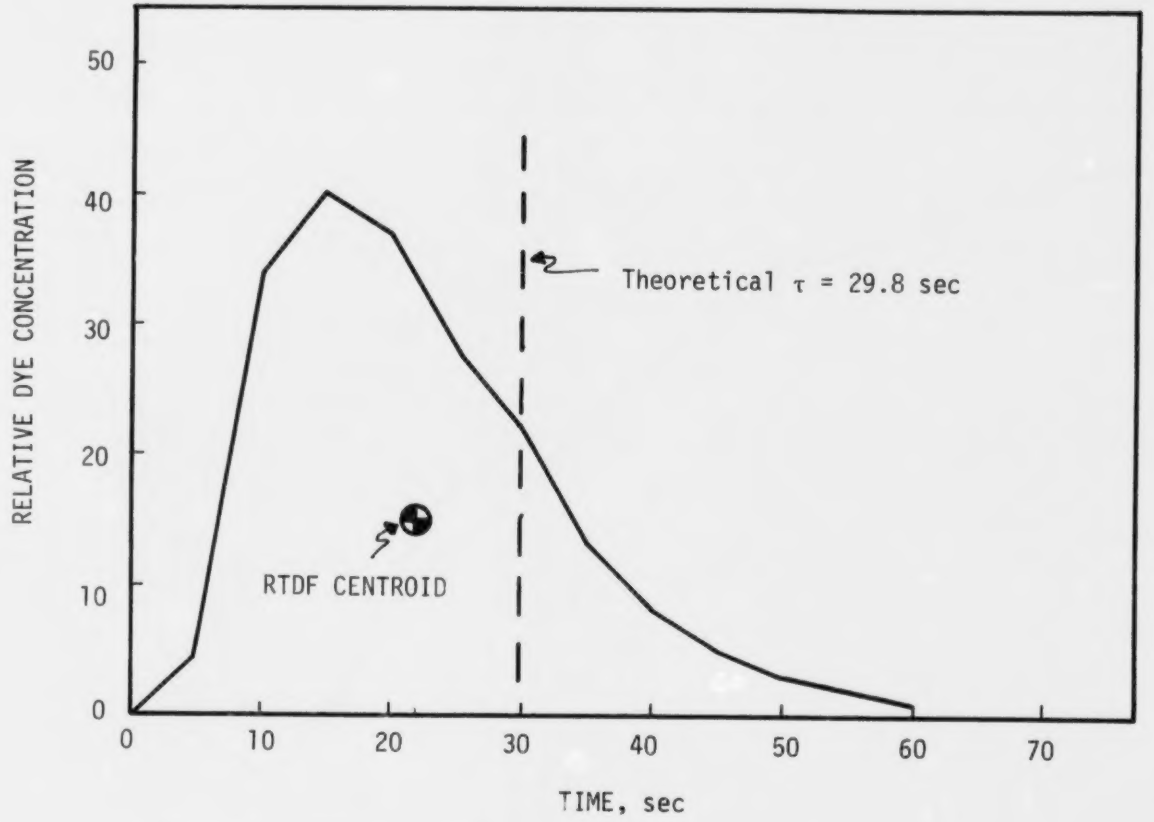


Figure 49. RTDF for UPS unit at 1.89 liters/sec.

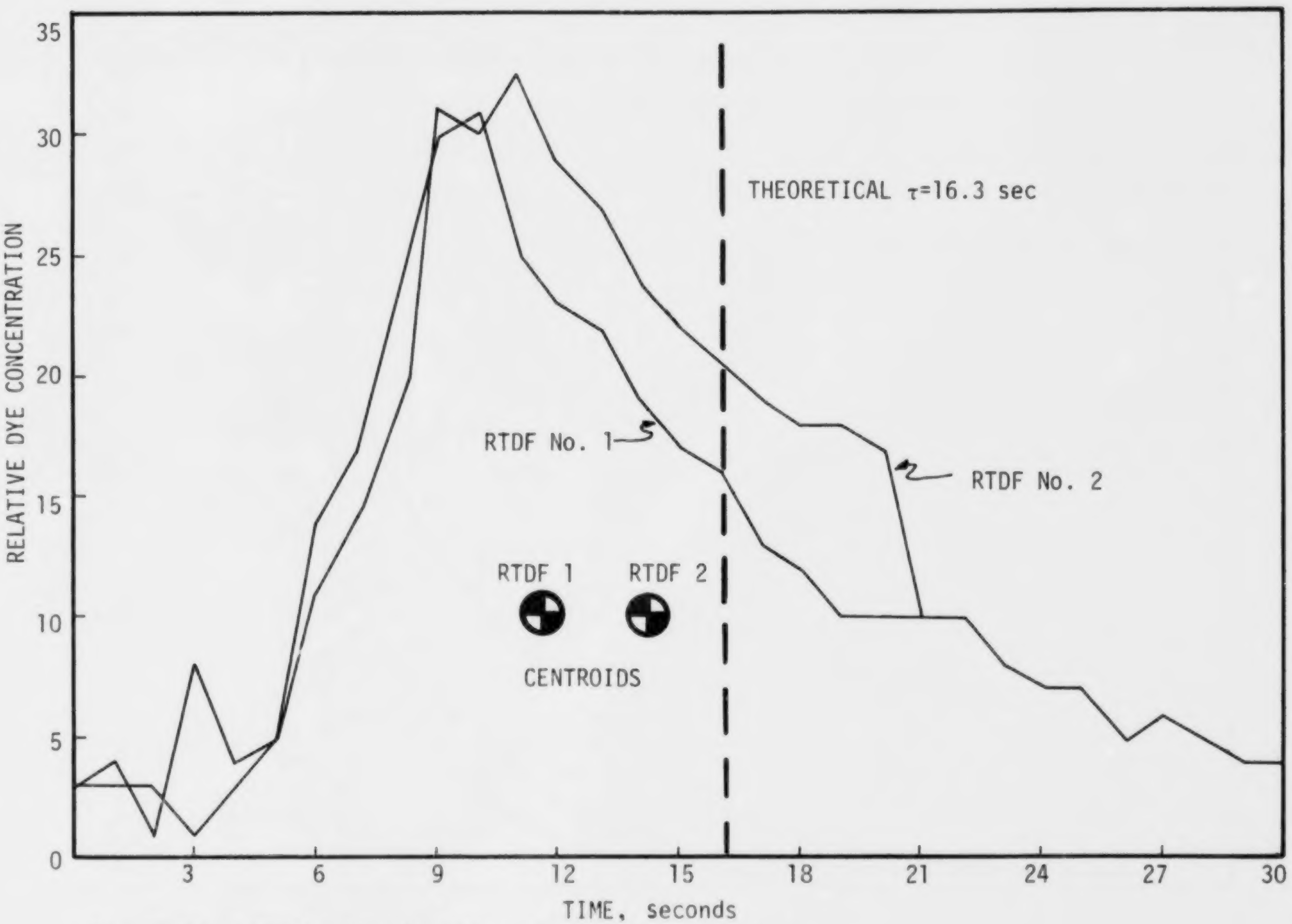


Figure 50. RTDF's for the UPS unit at 3.47 liters/sec.

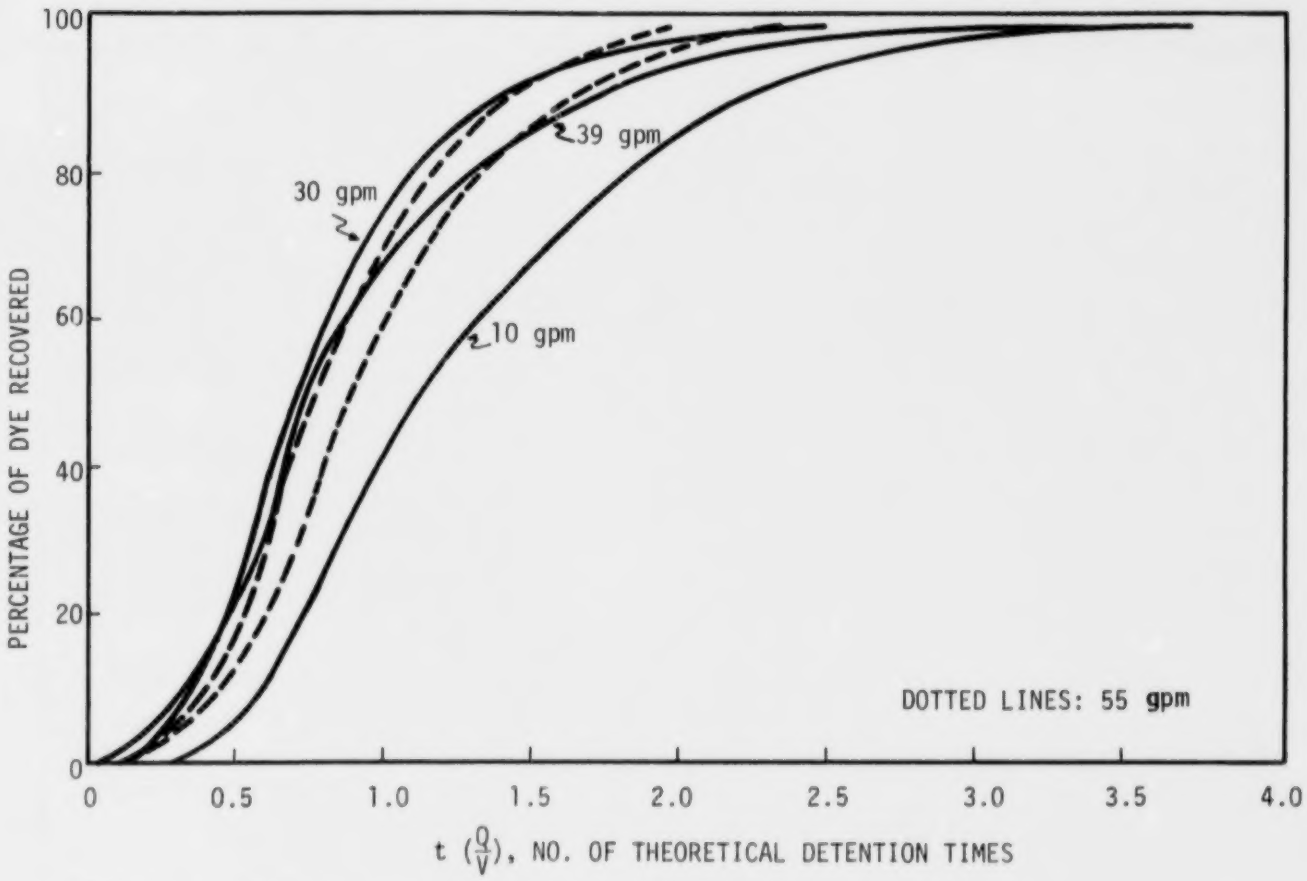


Figure 51. Cummulative dimensionless RTDF's for the UPS unit.

evident in the 0.63 liter/sec. RTDF's.

The hydraulic performance of the UPS unit was generally good. The dye studies indicated that at a flow of 3.47 liter/sec an organism could possibly exit the UV exposure chamber after only a 3-second exposure. This is indicative of short circuiting. Tailing was observed at all flows. In theory plug flow was not approached very closely; however, in practice the unit performed about as well as can be expected from a very short residence time unit.

DETERMINATION OF DOSE

Most UV dose data reported in the literature are in units of μwatt-sec per cm^2, and considering the experimental procedures employed in early research efforts the dose units are reasonable. The majority of the commercial UV irradiation chambers presently manufactured are totally enclosed. The absence of a free water surface that is relatively uniformly irradiated makes the determination of the average UV intensity in the water almost impossible. In an enclosed chamber with more than one UV lamp, the UV intensity within the water being irradiated will vary from point to point. This variation could not be quantified with the instrumentation available during the time period in which the project was conducted.

With a totally enclosed irradiation chamber it is very easy to measure the energy applied per unit volume of water per unit time, but it is not possible to measure the average UV energy reaching a unit volume of water per unit time. During this project UV dose within the UPS unit was not directly measured. In an effort to overcome this deficiency, several different approaches were taken in estimating the UV dose under differing experimental conditions.

An actinometry procedure described by Parker (11), and by Calvert and Pitts (12) was investigated to check the output of the UV lamps, and provided excellent results. In this procedure the iron (III) in potassium ferrioxalate is reduced to iron (II), while the oxalate ion is oxidized. The resulting color change is measured by a conventional spectrophotometer. Data from actinometric experiments performed in distilled water indicated that 117.6 joules per second of UV energy were being produced by the nine 40-watt lamps. These data indicated that approximately one-third of the energy supplied to the lamps was emitted in the UV region. This value agrees reasonably well with the 37 percent efficiency claimed by the manufacturer.

The only dose related parameter that could be measured easily and on a routine basis was the UV light intensity at a quartz window on the side of the UPS unit. The window was surrounded by a 2.54 cm (1 inch) diameter 316 stainless steel pipe that was 6 cm (2.4 inches) long. Intensity measurements were made with the previously described IL 500 radiometer. Since the sensor used for the IL 500 was larger than the pipe projecting from the quartz window, some of the radiation reaching the window was blocked from reaching the IL 500 sensor. As a result of this geometry, the UV intensity readings taken with the IL 500 were low.

An experiment was conducted to determine the effect of the system geometry on the intensity values measured. Data indicated that the measured values should be multiplied by a factor of 8.9 to obtain correct intensity values.

In order to compute dose in units of energy per unit area it was necessary to know the average UV intensity within the exposure chamber. With the technology then available it was not possible to directly determine or measure the average intensity (or dose) in a totally enclosed exposure chamber. The procedure described below was used to compute a mean UV intensity within the UPS unit.

1. A relative intensity of 1.0 at the surface of the quartz sleeves, and no attenuation of the UV light were assumed. The UV intensity at various distances from each lamp was then computed. The computation assumed the lamp functioned as a line source, and the result was a set of concentric lines of equal intensity around each lamp; however, the intensity patterns represented in this manner indicate the effect of only one lamp.

2. Several lamps influenced the actual intensity at any point within the contactor. To consider this effect the intensity values for each lamp, at any given point, were summed. The resultant number was the intensity at a given point relative to the intensity at the surface of the quartz sleeves. Therefore a relative intensity value of 1.3 would indicate that the calculated intensity at that point was 130 percent of the UV intensity at the surface of the quartz sleeves. The effects of shadowing were considered in the computation of relative intensity values.

3. Relative intensity values were computed for several hundred discrete points on the transverse cross section of the exposure chamber. Points of equal intensity were connected such that isointensity lines were developed as shown in Figure 52.

4. The average, relative UV intensity within the exposure chamber was then easily computed by planimetering the areas between adjacent isointensity lines, and multiplying by the average UV intensity between the isointensity lines. This resulted in an area-intensity product.

   The area-intensity products were computed for the total cross section, and summed. The sum of the area-intensity products divided by the total area yielded the mean relative intensity

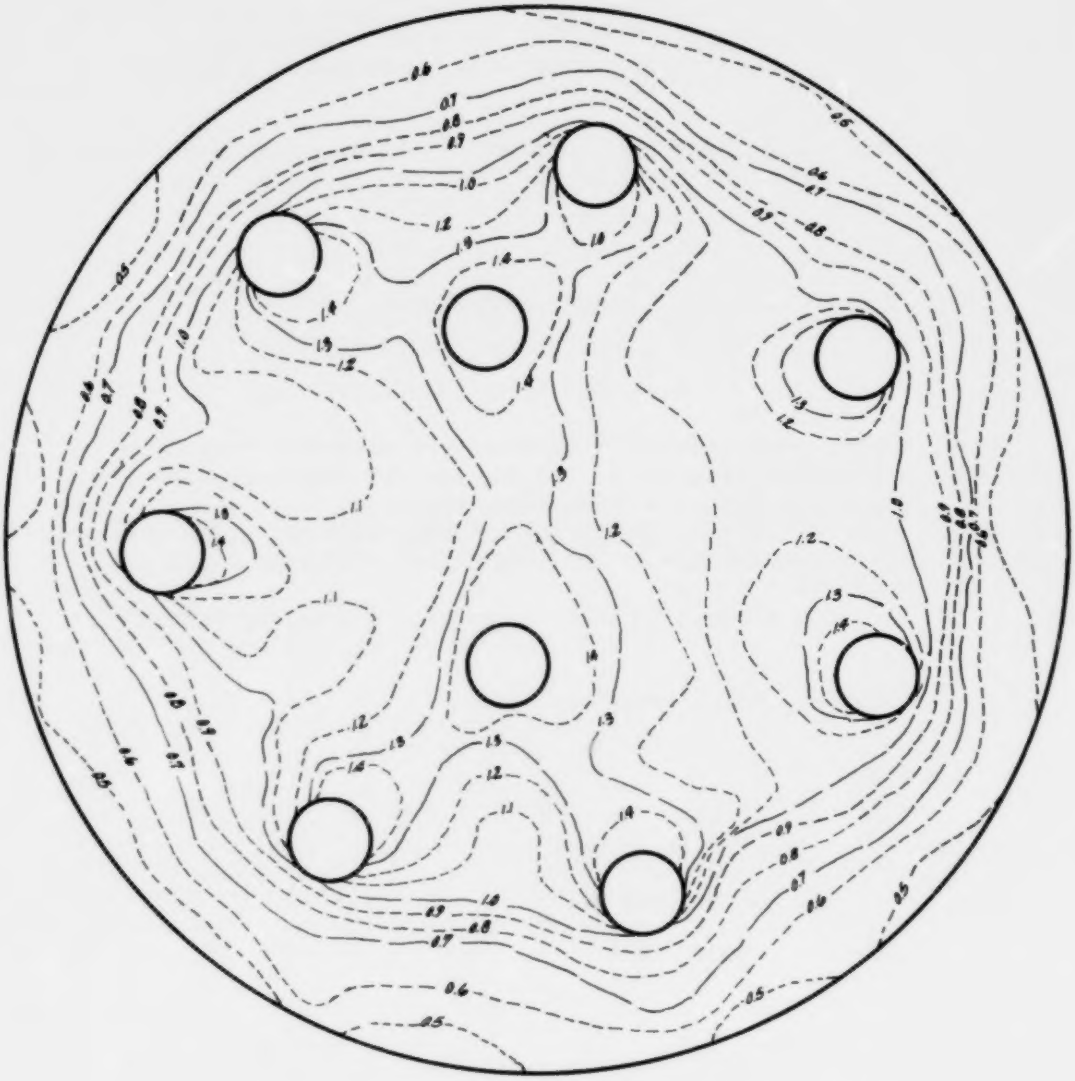

0.6
0.7
0.8
0.9
0.5
1.0
1.2
1.3
1.4
1.1

Figure 52. Isointensity patterns for UPS exposure chamber.

within the exposure chamber.

5. The mean relative intensity computed in this manner was 1.1, and the intensity measured at the surface of a quartz sleeve (lamp and sleeve removed from unit) was 4.6×10^{-3} watts per cm^2. The resultant average intensity within the exposure chamber was 5.06×10^{-3} watts per cm^2, but this value assumed that there was no attenuation occurring.

In order to compute the actual average UV intensity within the exposure chamber attenuation was considered by utilizing the following equation.

$$I = I_o e^{-kd}$$

where I_o = 5060 μwatts/cm^2

k = extinction coefficient (cm^{-1})

d = mean light path length (cm)

The extinction coefficients for various runs were determined from the transmittance values measured at 254 nm, and the mean path length of the UV light within the exposure chamber was estimated to be 4.0 cm. Dose can be simply computed by multiplying the average intensity value obtained by the procedure just described by the theoretical residence time.

example: Given - flow = 2.0 liters/sec (32 gpm)
transmittance @ 254 mm = 62 percent

1. Calculate the average intensity, I:

$$I = I_o e^{-kd}$$
$$= 5060 \quad e^{-0.5\,(4.0)}$$
$$= 5060\ (0.135)$$
$$= 683\ \mu\text{watts/cm}^2$$

2. Calculate theoretical residence time, τ:

$$\tau = \frac{v}{q}$$
$$= \frac{53.6\text{ liters}}{2.0\text{ liters/sec}}$$
$$= 26.8\text{ sec}$$

3. Calculate dose, D_T:

$$D_T = I \times \tau$$

$$= \frac{683\ \mu\text{watts}}{\text{cm}^2} \times 26.8\ \text{sec.}$$

$$= 18{,}300\ \mu\text{watt-sec/cm}^2$$

When the UV dose was calculated in the above manner the effect of slime accumulation on the quartz sleeves surrounding the UV lamps was not considered; furthermore, the theoretical residence time was used in lieu of the actual residence time. The only two variables affecting the UV dose which enter the above calculations are the flow rate and the extinction coefficient. Figure 53 presents the calculated dose, D_T, as a function of both of these variables.

The dose variation as a function of flow rate, within the practical operating range of the UPS unit (1.5 to 3.2 liters per second), is insignificant relative to the change in dose as a function of the extinction coefficient. The water and its associated impurities appears to be the most important factor affecting UV dose in an operating system.

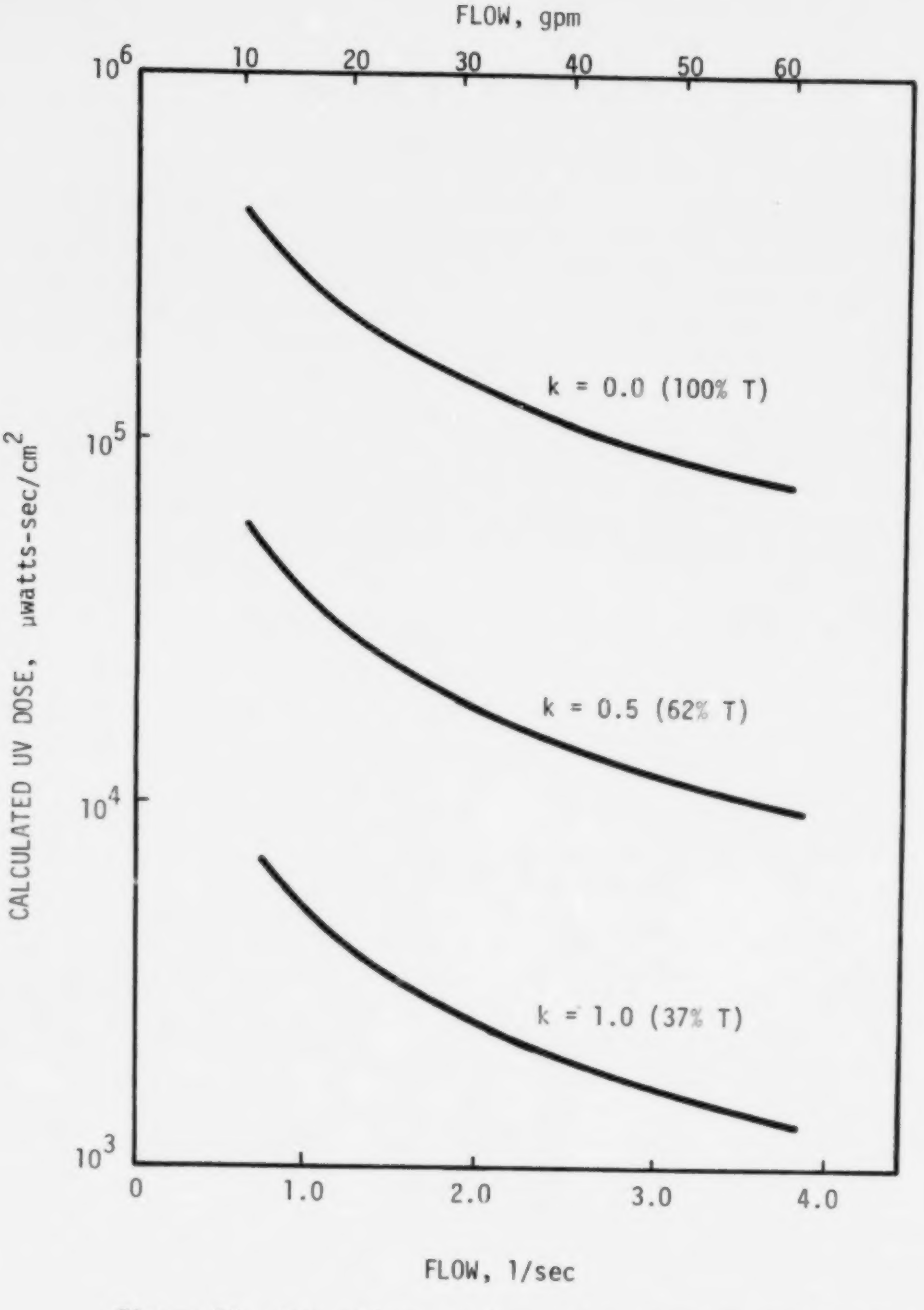


Figure 53. The effect of flow and extinction coefficient on the calculated UV dose.

RUN NO. U1

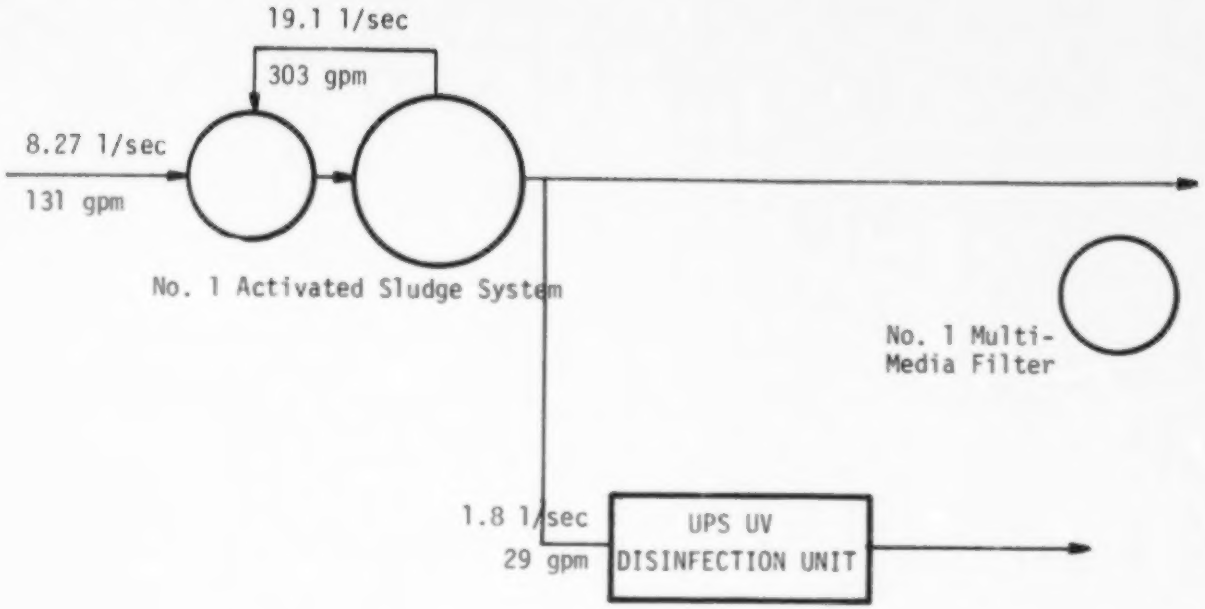
The first run with the Ultraviolet Purification Systems, Inc. UV disinfection unit was made between 23 January and 5 February 1975. The Demonstration Plant was configured as shown in Figure 54 for this study, with effluent from the No. 1 activated sludge system being pumped directly to the UPS unit at 1.8 liters/sec (29 gpm).

The nitrified activated sludge effluent during this period was of excellent quality, as the data presented in Table 17 indicate. Effluent TSS and COD concentrations averaged 17 and 33 mg/l, respectively. Nitrification was almost complete with only 2.2 mg/l of ammonia nitrogen in the effluent, and the reduction in total nitrogen averaged approximately 45 percent.

The data obtained from the grab samples collected for microbiological analysis are presented in Table 18. The percent transmittance values were determined at 254 nm on a Beckman DU spectrophotometer using a quartz cuvette with a 10-mm light path. The effluent geometric mean total and fecal coliform densities were less than 4.7 per 100 ml and 2.3 per 100 ml, respectively, indicating that excellent disinfection was achieved. Greater than four log reductions in coliform numbers were achieved, while only a 2.26 log reduction in standard plate count occurred in Run U1. Figures 55, 56, and 57 are time series plots of the microbiological data.

During this run the average flow rate of 1.8 liters/sec resulted in a theoretical residence time of 29.8 sec. The mean transmittance of 70.0 percent corresponded to an extinction coefficient of 0.35 cm^{-1}. The theoretical calculated dose, based on these operational parameters, was 37,200 μwatt-sec/cm^2. This was one of the highest doses utilized during the project and the UPS unit provided excellent disinfection under these conditions.

Extreme value frequency distributions for the microbiological data are presented in Figure 58, 59, and 60. Examination of the fecal coliform data in Figure 60 indicates a probability of 0.1 for finding a fecal coliform count exceeding 200 per 100 ml under the conditions of this run. Expressed in another way, the curve indicates that a fecal coliform count greater than 200 per 100 ml could be expected once in 1000 days, or once in about 2.7 years assuming the same wastewater quality and UV dosage conditions.



19.1 l/sec
303 gpm
8.27 l/sec
131 gpm
No. 1 Activated Sludge System
No. 1 Multi-Media Filter
1.8 l/sec
29 gpm
UPS UV DISINFECTION UNIT

Figure 54. Pilot Plant configuration during Run No. U1.

TABLE 17. PERFORMANCE OF THE NO. 1 ACTIVATED SLUDGE SYSTEM DURING RUN NO. U1

Parameter	Influent mg/l	Effluent mg/l	Removal percent
TSS	75	17	77
COD	203	33	84
TOC, soluble	37.6	9	76
NH_3-N	14.4	2.2	85
Org.-N	7.1	2.4	66
NO_2&NO_3-N	0.6	7.6	-
Total N	22.0	12.1	44.5
Total P	6.6	5.3	20
Turbidity, NTU	3.4	3.5	-
Color, Pt-Co units	32.5	24	-

TABLE 18. RESULTS OF RUN U1

Parameter	Influent					Effluent					
	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow, 1/sec	16	0.63	2.46	1.83	-	-	-	-	-	-	-
Turbidity,NTU	6	2.4	4.5	3.4	-	6	2.9	4.0	3.6	-	-
TSS, mg/1	6	3	10	7	-	6	4	8	7	-	-
Color, Pt-Co Units	8	15	50	33	-	8	10	40	26	-	-
TOC, mg/1	6	3	9	6	-	6	3	8	6	-	-
COD, mg/1	6	15	22	17	-	5	16	22	18	-	-
Percent Transmittance at 254 nm	6	60.3	76.7	70.7	-	-	-	-	-	-	-
Standard Plate Count per ml	12	$8.9x10^{3}$	$1.2x10^{5}$	$3.5x10^{4}$	4.54	11	$7.4x10^{1}$	$5.8x10^{2}$	$1.9x10^{2}$	2.28	2.26
Total Coliform per 100 ml	19	$3.3x10^{4}$	$1.0x10^{6}$	$1.3x10^{5}$	5.11	19	$<2.0x10^{0}$	$1.1x10^{2}$	$<4.7x10^{0}$	<0.67	>4.44
Fecal Coliforms per 100 ml	19	$1.1x10^{4}$	$4.9x10^{5}$	$3.7x10^{4}$	4.57	19	$<2.0x10^{0}$	$1.7x10^{1}$	$<2.3x10^{0}$	<0.36	>4.21

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

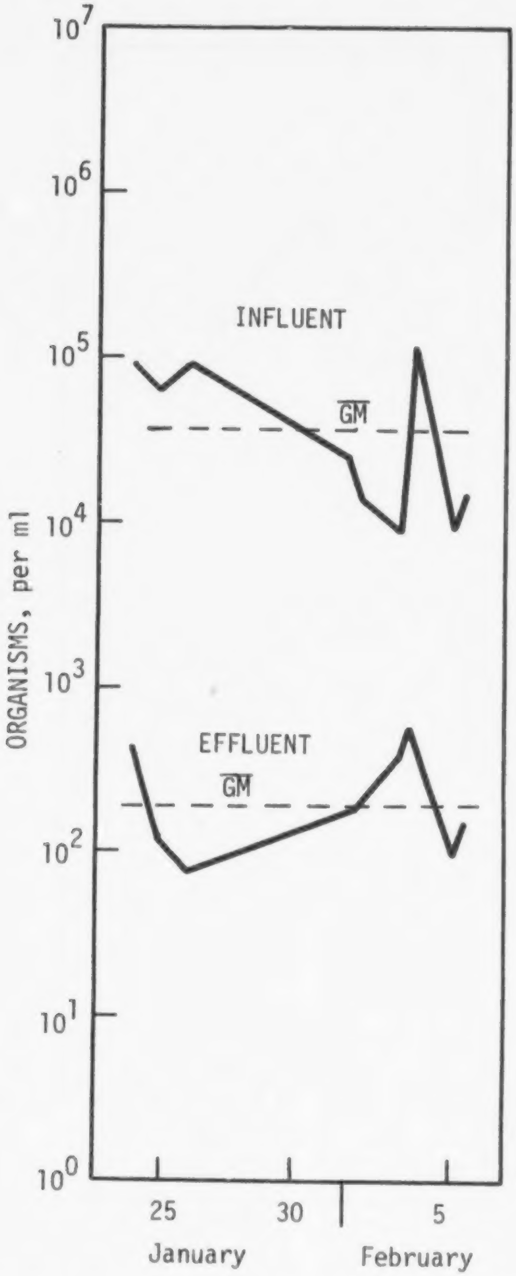


Figure 55. Standard plate count data for Run No. U1.

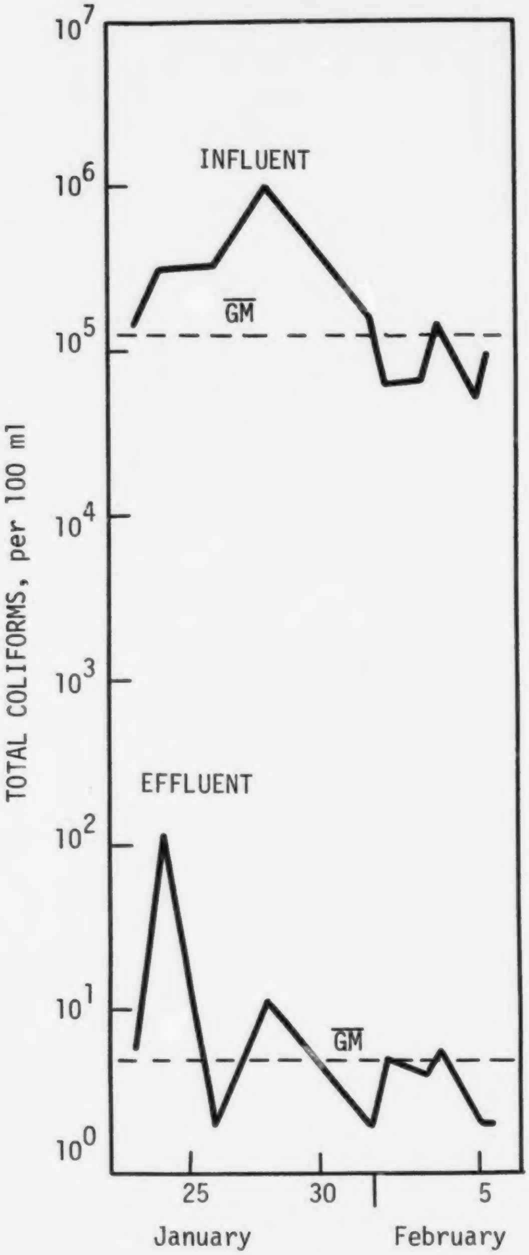


Figure 56. Total coliform data for Run No. U1.

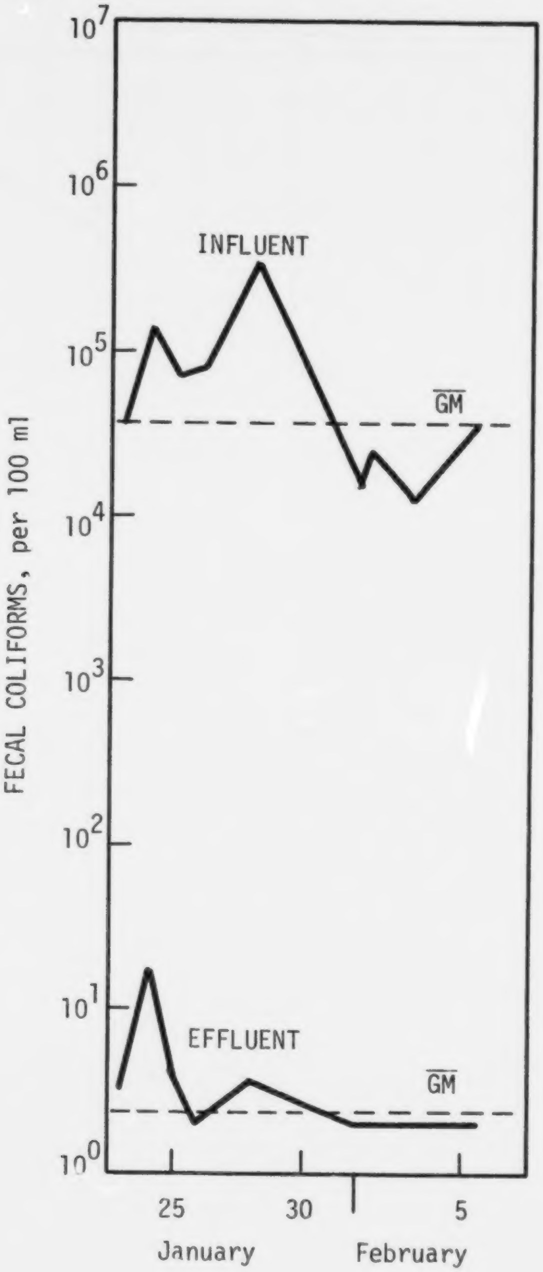


Figure 57. Fecal coliform data for Run No. U1.

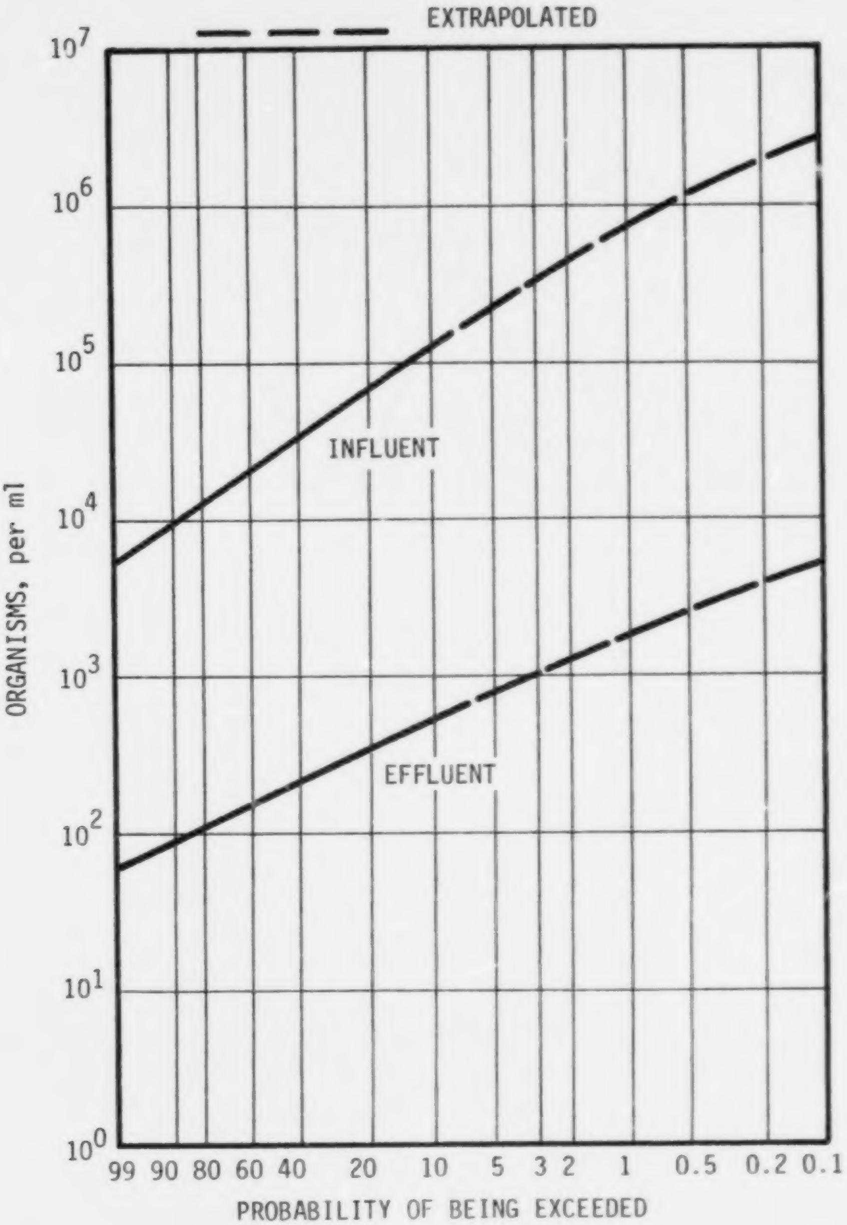


Figure 58. Extreme-value frequency distribution of standard plate count data for Run No. U1.

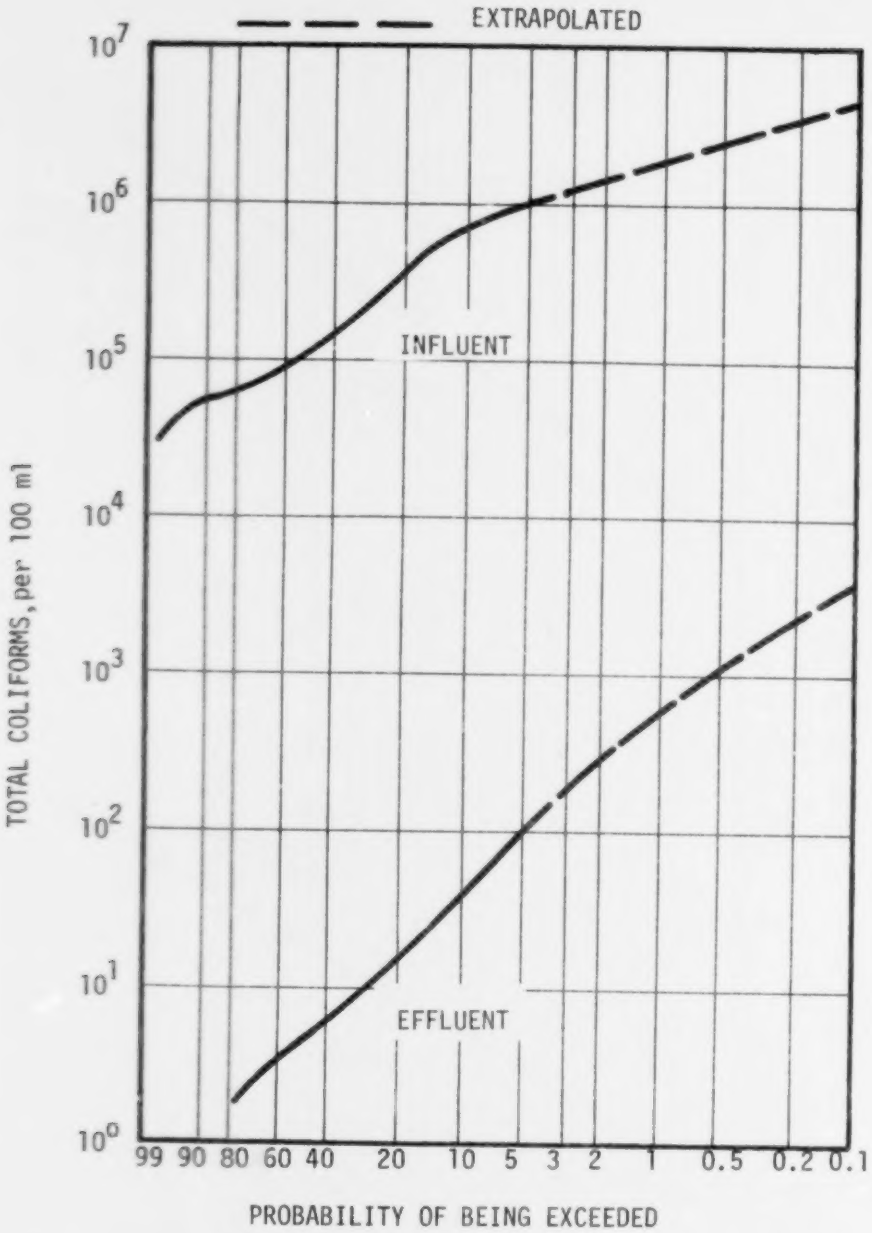


Figure 59. Extreme-value frequency distribution of total coliform data for Run U1.

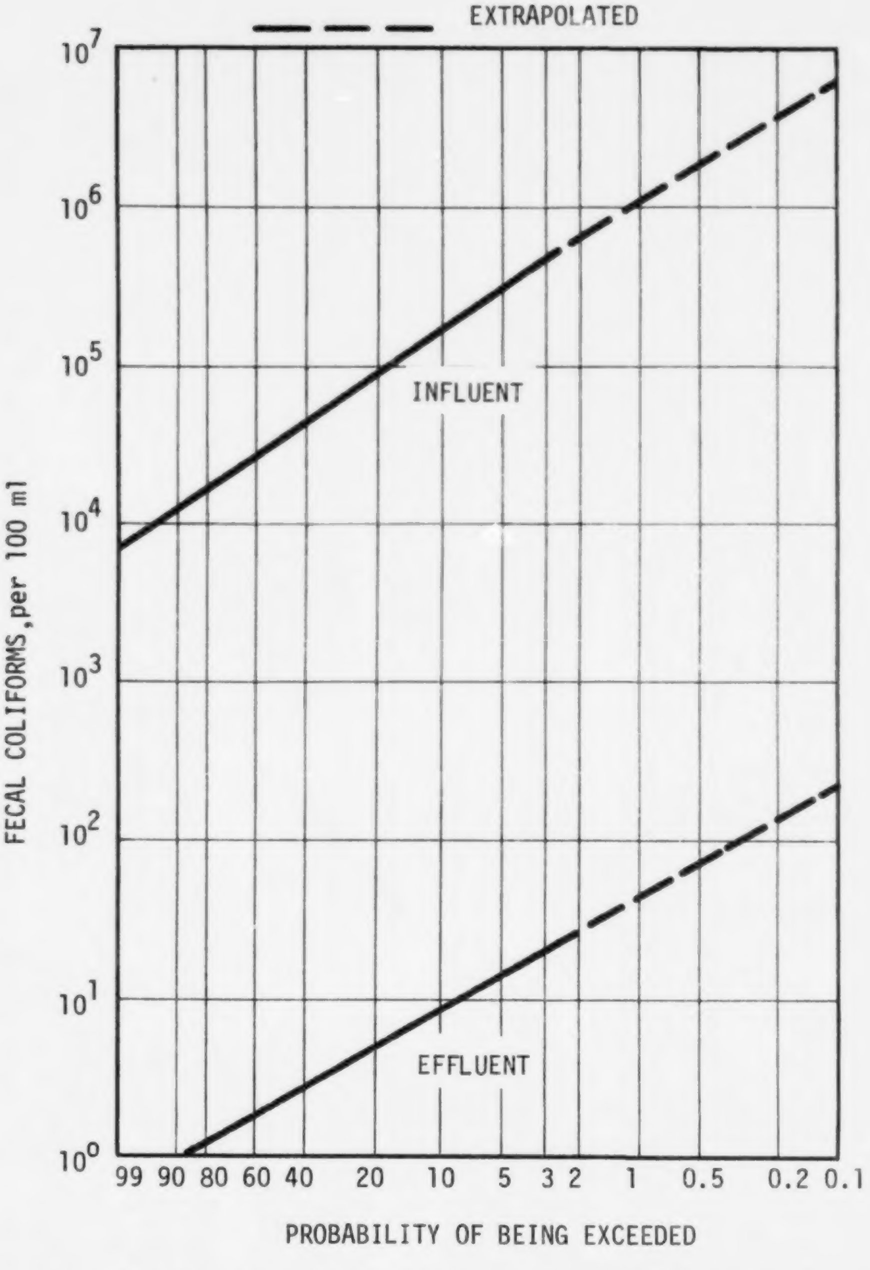


Figure 60. Extreme-value frequency distribution of fecal coliform data for Run U1.

RUN NO. U2

Run No. U2 was conducted during 7-17 February 1975. As shown in Figure 61, the effluent from the No. 1 activated sludge system was pumped to the upflow clarifier (Infilco Densator) at a flow of 6.30 liters/sec (100 gpm). The upflow clarifier was operated as a tertiary settling basin only, and no coagulants or coagulant aids were utilized during the run. The process configuration was selected so that the effect of additional treatment, obtained by the tertiary settling of the activated sludge effluent, could be evaluated.

The data presented in Table 19 summarize the performance of the Demonstration Plant during Run U2. During this time the activated sludge process was producing a good quality effluent. Effluent COD, soluble TOC, and ammonia-N concentrations averaged 35, 8, and 1.6 mg/l, respectively. The tertiary settling did very little to enhance effluent quality. COD was reduced from 35 to 24 mg/l, color was reduced by 10 Pt-Co units, and turbidity was unaffected.

During the run the UPS unit was operated at an average flow of 1.9 liters/sec (30 gpm), which resulted in a theoretical residence time of 28.2 seconds. The transmittance measured at 254 nm was 71.8 percent, which corresponds to an extinction coefficient of 0.34 cm^{-1}. The theoretical, calculated dose, D_T, for this run was 36,600 μwatts-sec/cm^2. The mean intensity at the quartz window was 1200 μwatts/cm^2, after the reading had been corrected for geometry. This value (1200 μwatts/cm^2) multiplied by the actual residence time of 25 seconds yields a dose related value of 30,500 μwatt-sec/cm^2. Since this value is a measured intensity value multiplied by the actual detention time it is very closely related to the actual UV dose. This term will be referred to as the indicated dose, D_I.

The data obtained from the grab samples collected for microbiological analyses are presented in Table 20. Excellent disinfection occurred. The geometric mean fecal and total coliform densities were less than 3.1 and 7.5 per 100 ml, respectively. Total and fecal coliform log reductions exceeded 4.0, while the mean standard plate count reduction was less than 2.0.

The time series plots of the microbiological data presented in Figures 62, 63, and 64, are indicative of consistently good disinfection. Extreme-value frequency distributions for standard plate counts, total coliforms, and fecal coliforms are presented in Figures 65, 66, and 67, respectively.

RUN NO. U3

Run No. U3 was conducted from 19 February 1975 to 3 March 1975. The Demonstration Plant was set-up as shown in Figure 68 for this run. The treatment was identical to Run No. U2, except the tertiary settled, activated sludge effluent was filtered prior to UV disinfection.

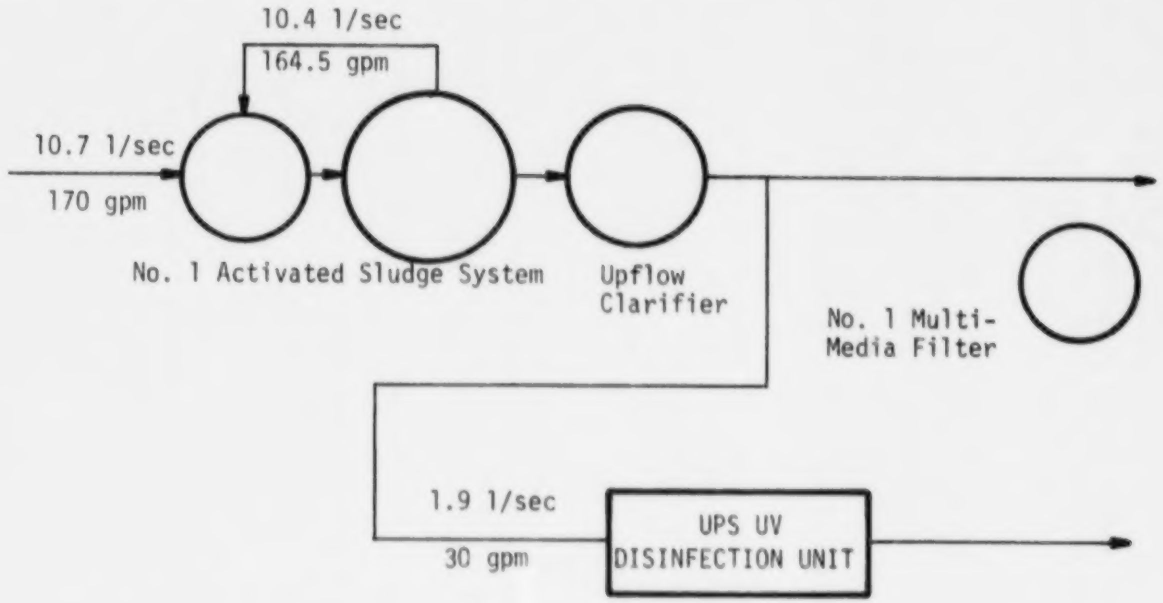

10.4 l/sec
164.5 gpm
10.7 l/sec
170 gpm
No. 1 Activated Sludge System
Upflow
Clarifier
No. 1 Multi-
Media Filter
1.9 l/sec
30 gpm
UPS UV
DISINFECTION UNIT

Figure 61. Pilot Plant configuration during Run No. U2.

TABLE 19. PERFORMANCE OF ACTIVATED SLUDGE AND TERTIARY SETTLING BASIN DURING RUN NO. U2

Parameter	A. S. Inf. mg/l	A. S. Eff. mg/l	Tertiary Settled Effluent mg/l	Removal percent
TSS	97.4	21.2	40.3	59.0
COD	199	35.0	24.4	88.0
TOC, soluble	31	8.1	7.9	75.0
NH_3-N	12.2	1.6	1.8	85.0
Org-N	7.3	2.5	2.0	73.0
NO_2 & NO_3-N	0.1	6.6	6.7	-
Total N	19.6	10.7	10.5	46.4
Total P	7.3	4.5	2.5	65.8
Turbidity, NTU	-	4.1	4.2	-
Color, Pt-Co units	-	19	16	-

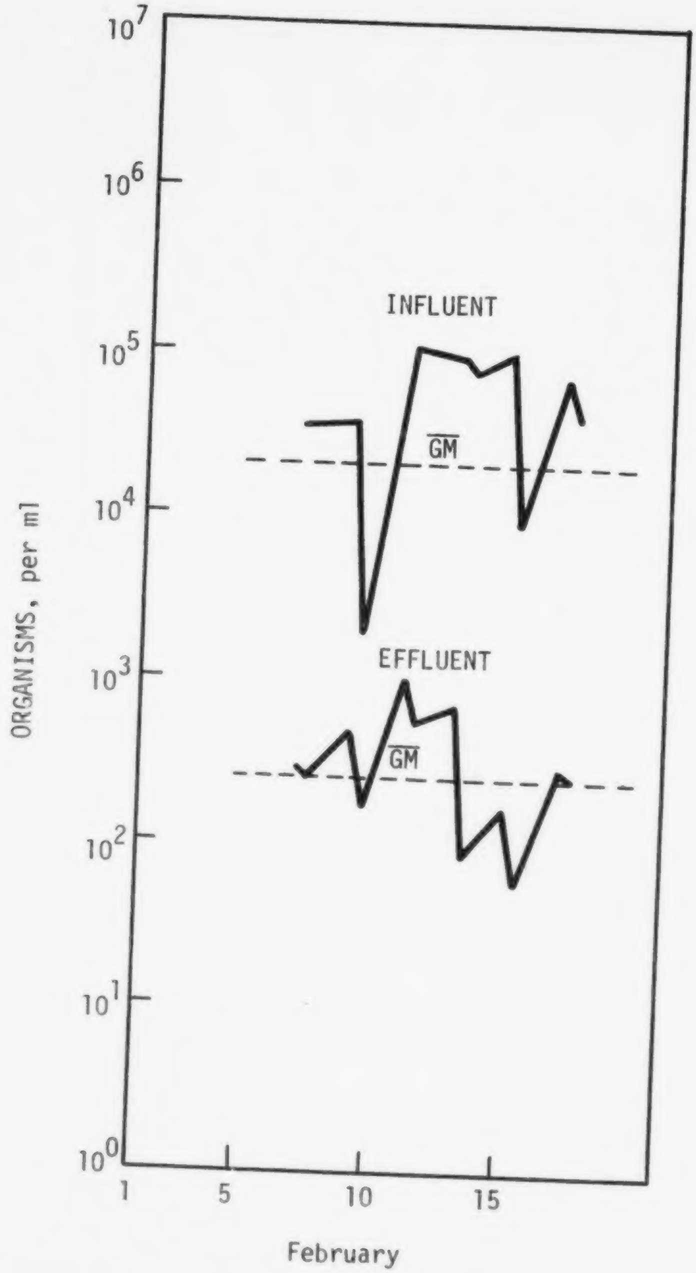


Figure 62. Standard plate count data for Run No. U2.

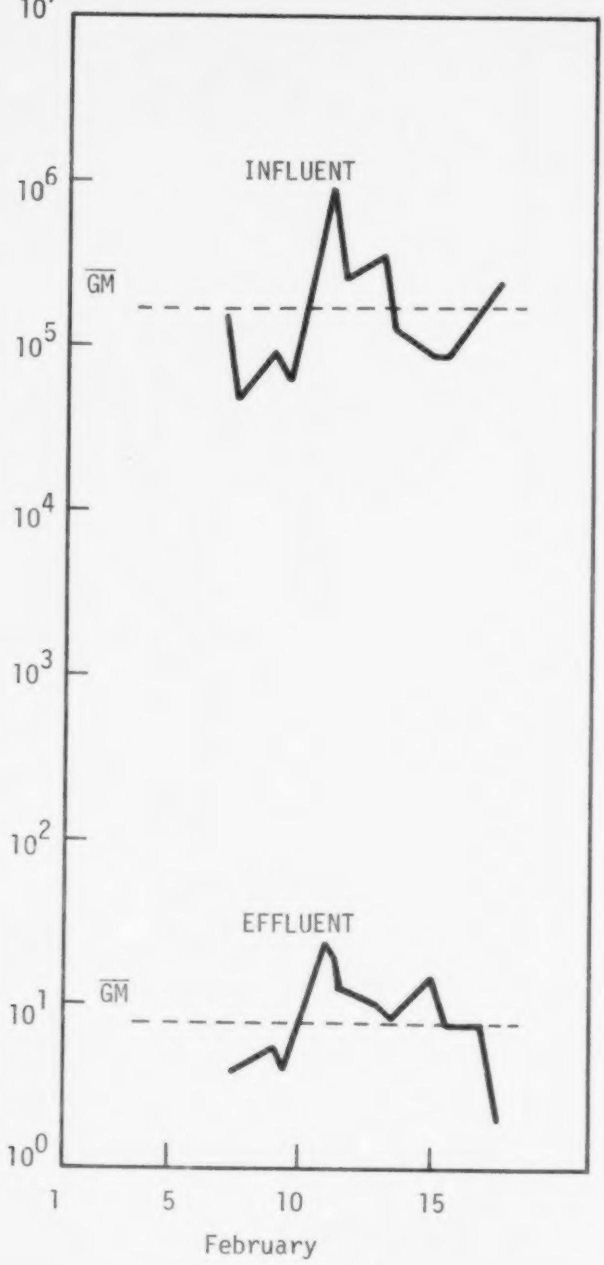


Figure 63. Total coliform data for Run No. U2.

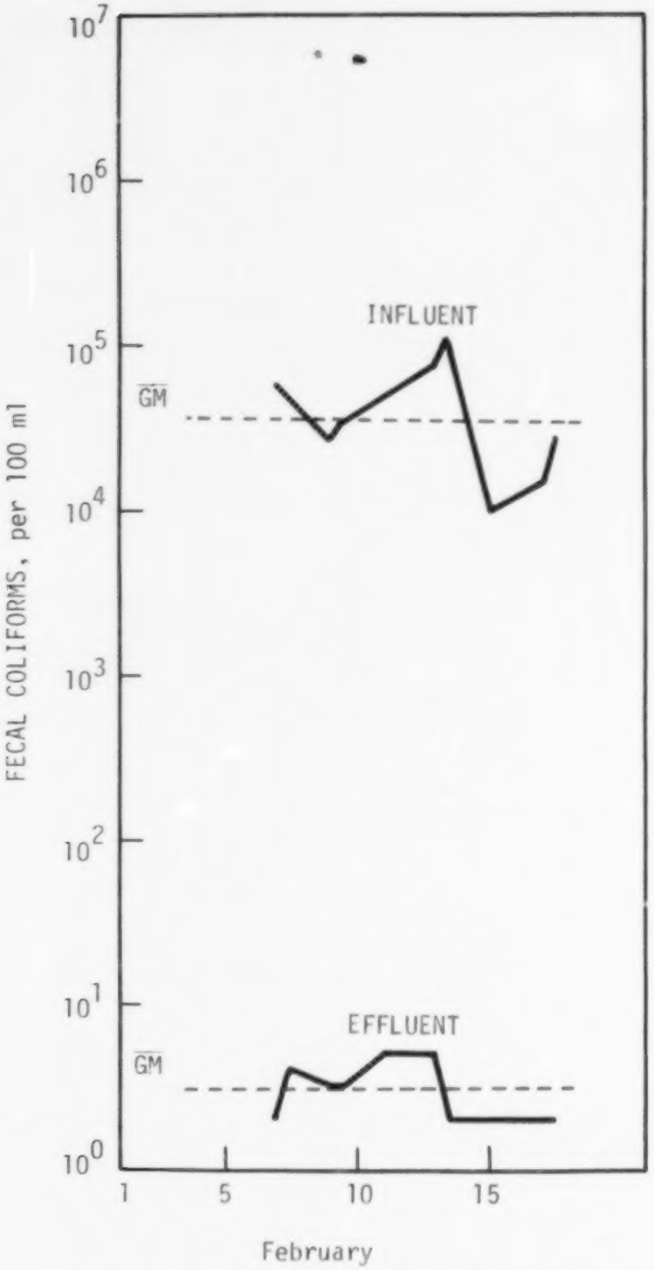


Figure 64. Fecal coliform data for Run No. U2.

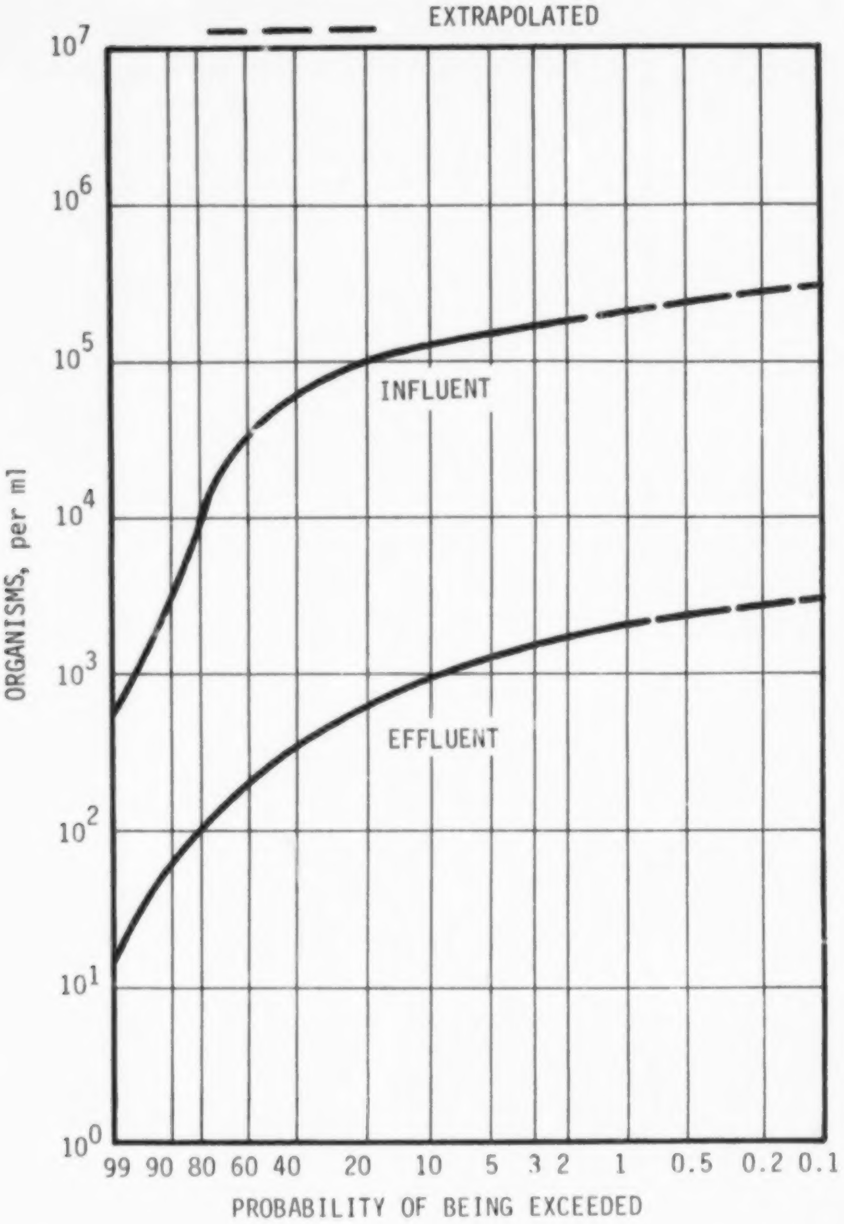


Figure 65. Extreme-value frequency distribution of standard plate count data for Run No. U2.

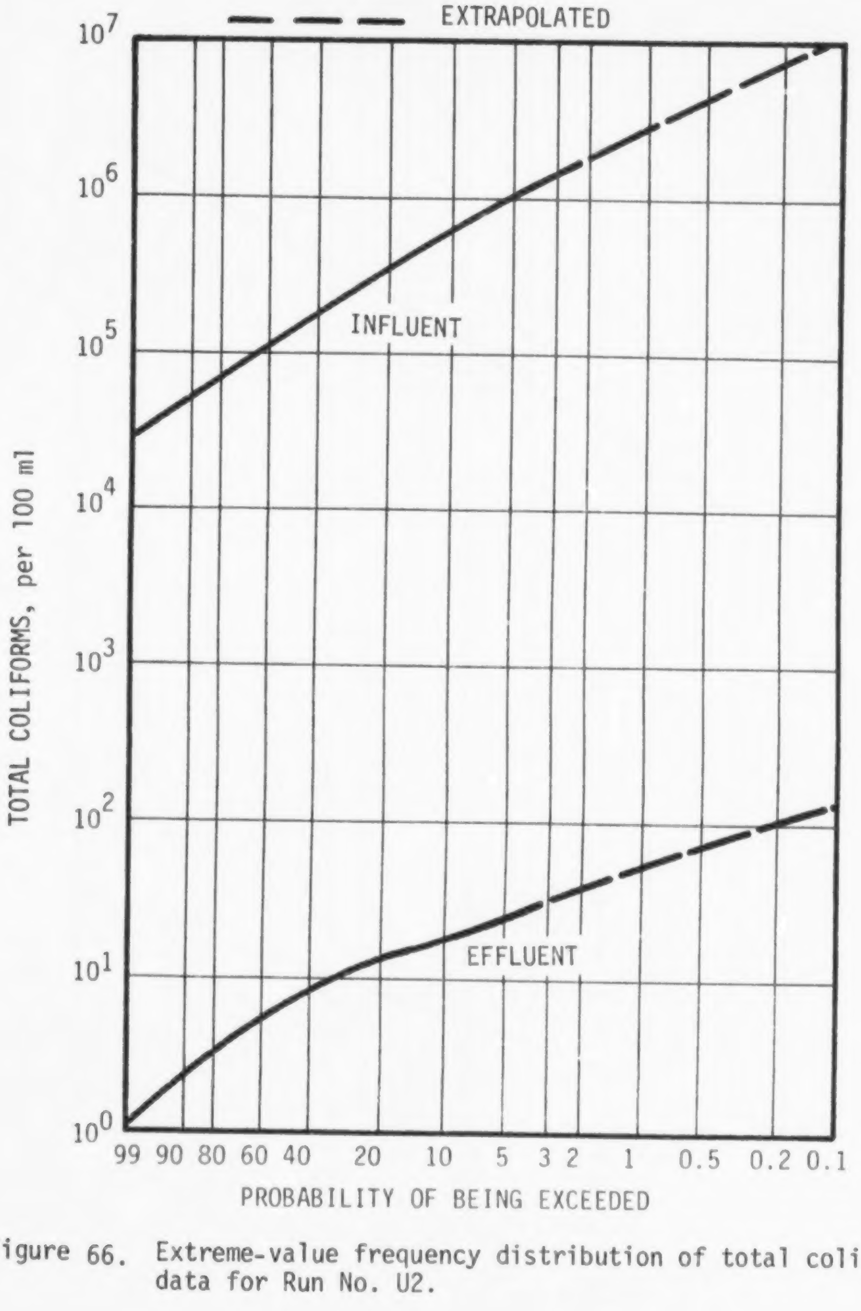


Figure 66. Extreme-value frequency distribution of total coliform data for Run No. U2.

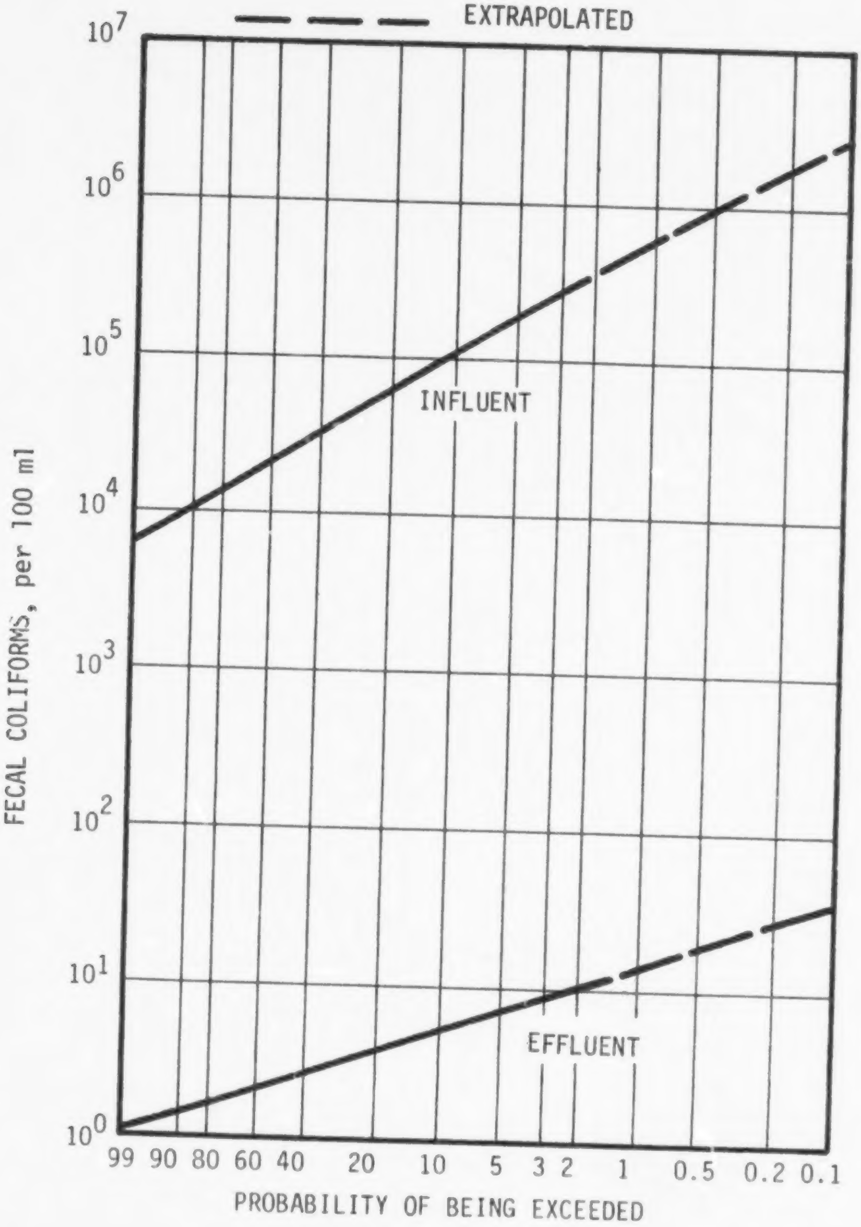


Figure 67. Extreme-value frequency distribution of fecal coliform data for Run No. U2.

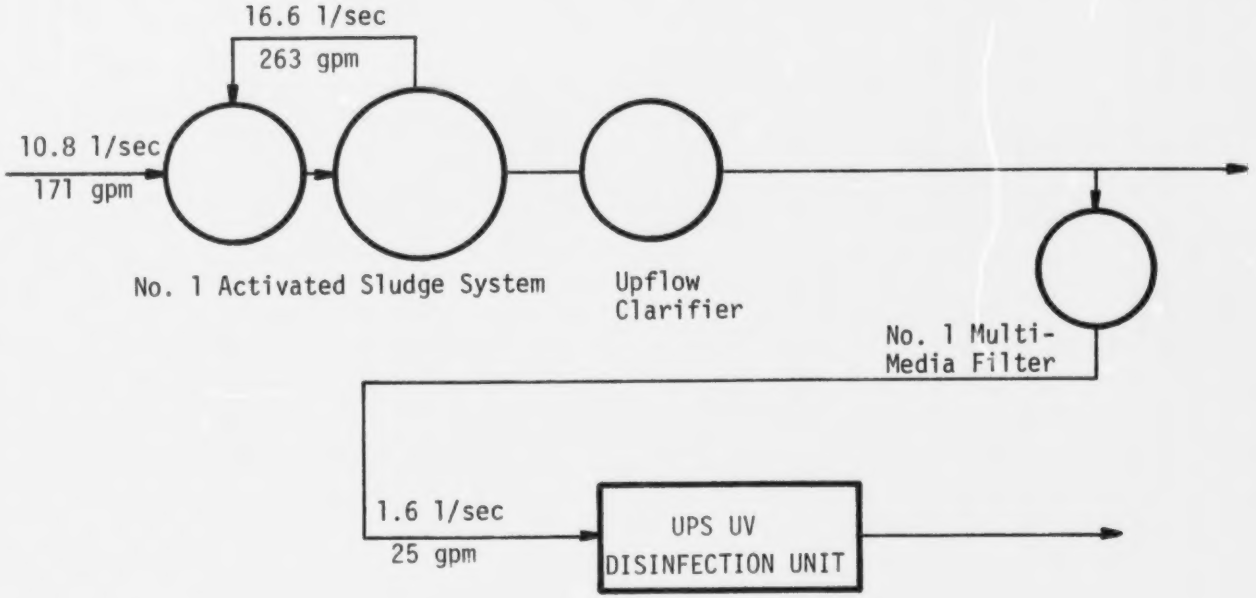

16.6 l/sec
263 gpm
10.8 l/sec
171 gpm
No. 1 Activated Sludge System
Upflow
Clarifier
No. 1 Multi-
Media Filter
1.6 l/sec
25 gpm
UPS UV
DISINFECTION UNIT

Figure 68. Pilot Plant process configuration for Run No. U3.

Water quality data for the various unit processes are summarized in Table 21. The No. 1 activated sludge system continued to achieve good nitrification and produce a high quality effluent,as the effluent TSS, COD, and ammonia-N concentrations of 28, 42, and 1.5 mg/l, respectively, indicate. As in the previous run the tertiary settling process did little to improve effluent quality; however, the filtration process did significantly enhance effluent quality. The filter lowered the mean TSS concentration from 32 mg/l to 4 mg/l, an 88-percent reduction, and effected a 46-percent reduction in effluent COD, from 42 to 23 mg/l.

During Run No. U3 the flow to the UPS unit averaged 1.6 liters/sec (25 gpm), which was approximately the same as in the two previous runs. This flow rate resulted in a theoretical residence time of 33.5 seconds, and an actual residence time of 29.5 seconds. The mean measured transmittance value of 68.9 percent was equivalent to an extinction coefficient of 0.38 cm^{-1}. The calculated mean dose, D_T, during the run was 37,100 μwatt-sec/cm^2, and the indicated dose, D_I, was 57,800 μwatt-sec/cm^2. The average reading on the IL 500 radiometer was 220 μwatts/cm^2, which corresponds to a mean intensity at the exposure chamber wall of 1960 μwatts/cm^2 when the original reading is corrected for system geometry.

Table 22 summarizes the data obtained from the microbiological samples. The geometric means for both the total and fecal coliforms were less than 2 per 100 ml. Greater than a five-log reduction was observed for total coliforms, and fecal coliforms were reduced by 4.22 logs. The standard plate count reduction was 2.32 logs.

The time series plots of the microbiological data presented in Figures 69, 70, and 71, graphically depict the excellent disinfection obtained during this run. Figures 72, 73, and 74, are the extreme-value frequency distributions.

The best disinfection observed during the project occurred during Run No. U3. Two factors contributed to the excellent results obtained; first, the quality of the wastewater effluent being disinfected was very good. However it should be noted that the lower mean TSS and COD concentrations obtained by filtration had no effect on the transmissability of UV light, since the precent transmittance at 254 nm observed during runs U1, U2, and U3 were practically identical. Second, the calculated doses, D_T, were highest during runs U1, U2, and U3 and the highest radiometer readings were obtained during Run U3.

RUN NO. U4

Run No. U4 was conducted 6-7 March 1975 to evaluate the effect of chemical coagulation/flocculation on UV disinfection. The Pilot Plant was configured as shown in Figure 75 The activated sludge effluent was pumped to the upflow clarifier, where ferric chloride was added as a coagulant. The chemically treated water then flowed by gravity to the UPS UV Unit.

TABLE 21. PERFORMANCE OF THE ACTIVATED SLUDGE SYSTEM AND MULTIMEDIA FILTER DURING RUN NO. U3

Parameter	A.S. Influent mg/l	A.S. Effluent mg/l	Tertiary Settled Effluent mg/l	No.1 Filter Effluent mg/l	Removal percent
TSS	95	28	32	4	96
COD	247	41.6	42.1	22.8	91
TOC, soluble	41.4	9.3	9.4	8.2	80
NH_3-N	14.0	1.5	1.5	1.1	92
Org.-N	8.0	3.2	2.4	1.6	80
NO_2 & NO_3-N	0.4	6.2	6.2	5.1	-
Total N	22.4	10.9	10.1	7.8	65
Total P	9.2	7.2	7.8	7.5	18
Turbidity NTU	-	-	2.0	1.9	-
Color Pt-Co units	-	-	17.5	17.9	

TABLE 22. RESULTS OF RUN U3.

	Influent					Effluent					
Parameter	N	Min	Max	Mean[1]	Log of Mean[1]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow, l/sec.	13	1.39	1.70	1.58	-	-	-	-	-	-	-
Turbidity, NTU	11	1.6	2.6	2.0	-	11	1.6	2.3	1.9	-	-
TSS, mg/l	13	1	8	2	-	13	1	7	2	-	-
Color, Pt-Co Units	12	10	20	18	-	12	10	20	18	-	-
TOC, mg/l	13	2	10	8	-	8	13	5	10	-	-
COD, mg/l	13	11	26	18	-	13	15	24	19	-	-
Percent Transmittance at 254 nm	8	65.6	71.1	68.9	-	-	-	-	-	-	-
Standard Plate Count per ml	8	6.2×10^3	5.0×10^4	1.6×10^4	4.20	16	3.7×10^1	2.1×10^2	7.5×10^1	1.88	2.32
Total Coliforms per 100 ml	26	3.3×10^4	5.4×10^6	2.0×10^5	5.30	24	$<2.0 \times 10^0$	$<2.0 \times 10^0$	$<2.0 \times 10^0$	<0.30	>5.00
Fecal Coliforms per 100 ml	26	5.0×10^3	2.3×10^5	3.3×10^4	4.52	24	$<2.0 \times 10^0$	$<2.0 \times 10^0$	$<2.0 \times 10^0$	<0.30	>4.22

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

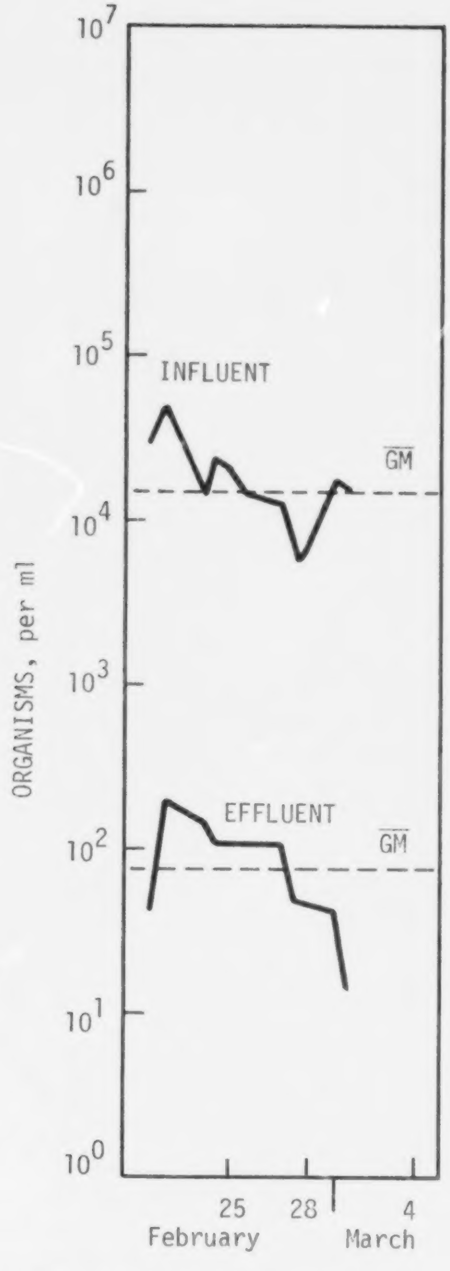


Figure 69. Standard plate count data for Run No. U3.

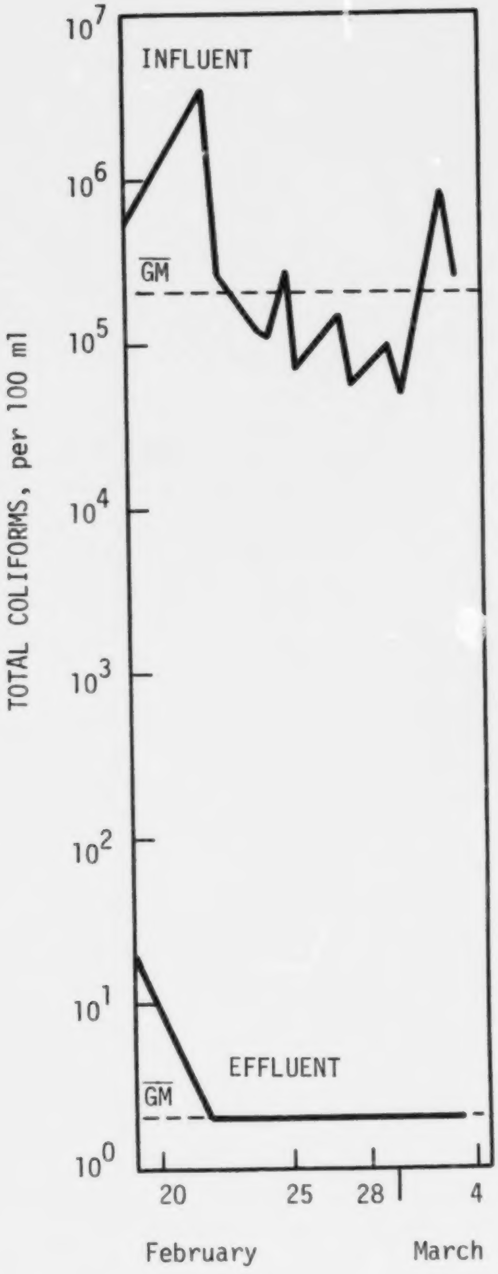


Figure 70. Total coliform data for Run No. U3.

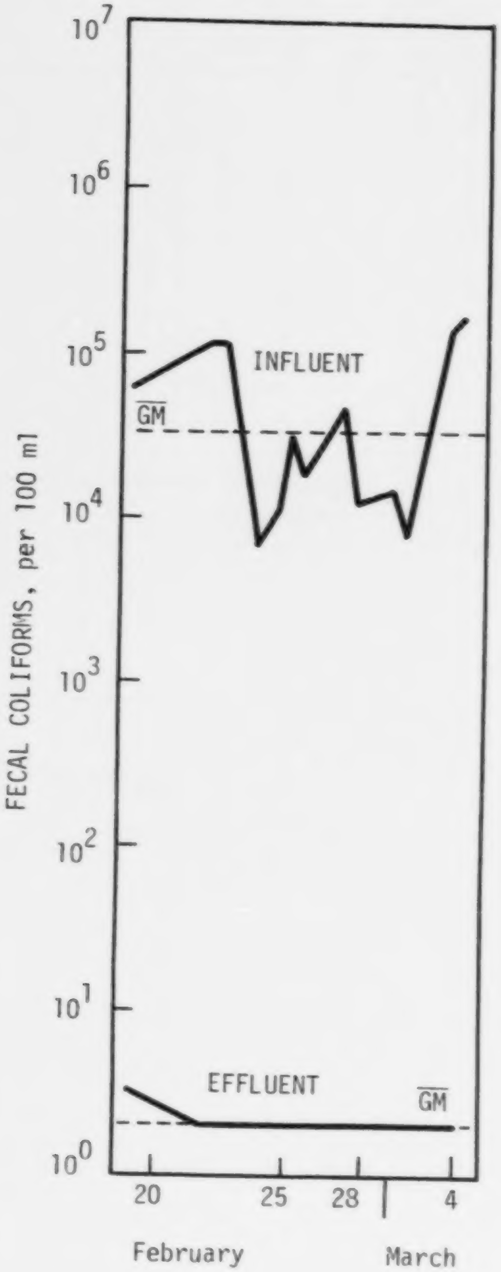


Figure 71. Fecal coliform data for Run No. U3.

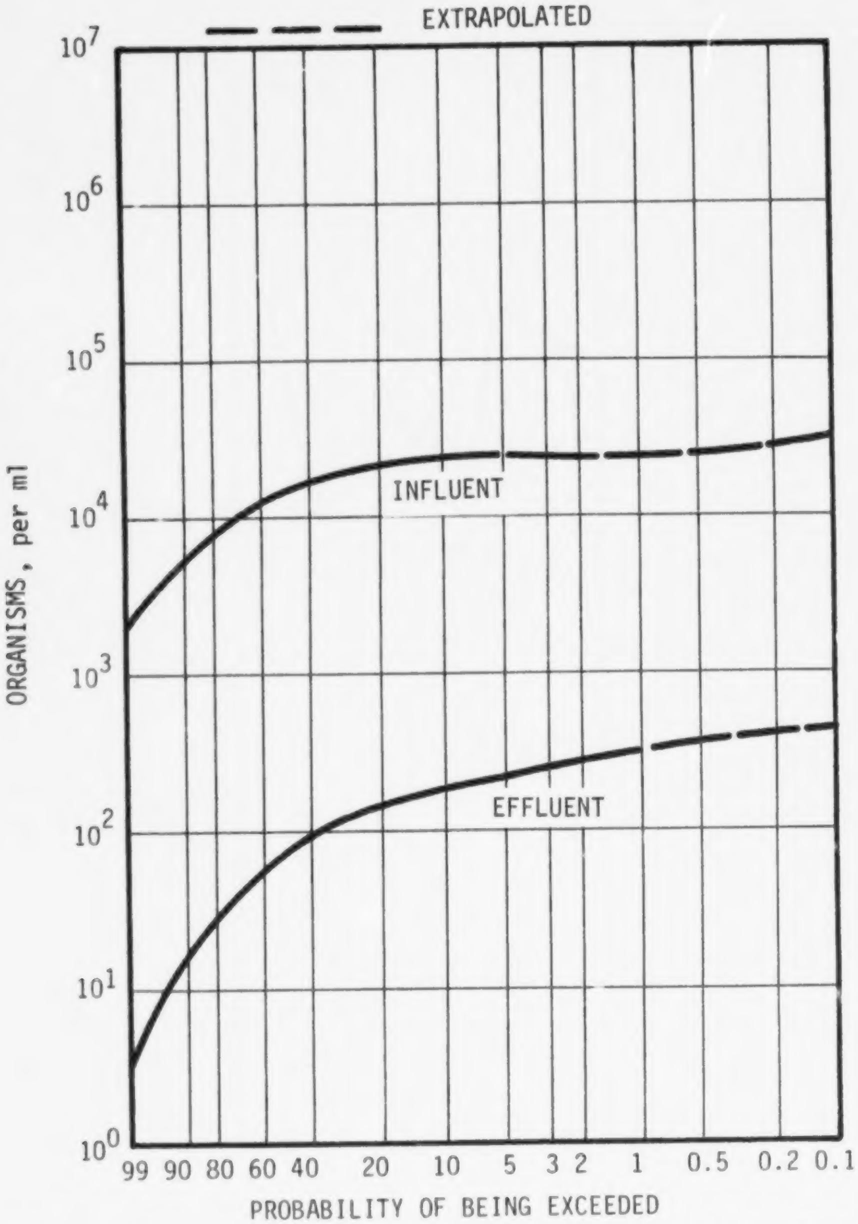


Figure 72. Extreme-value frequency distribution of standard plate count data for Run No. U3.

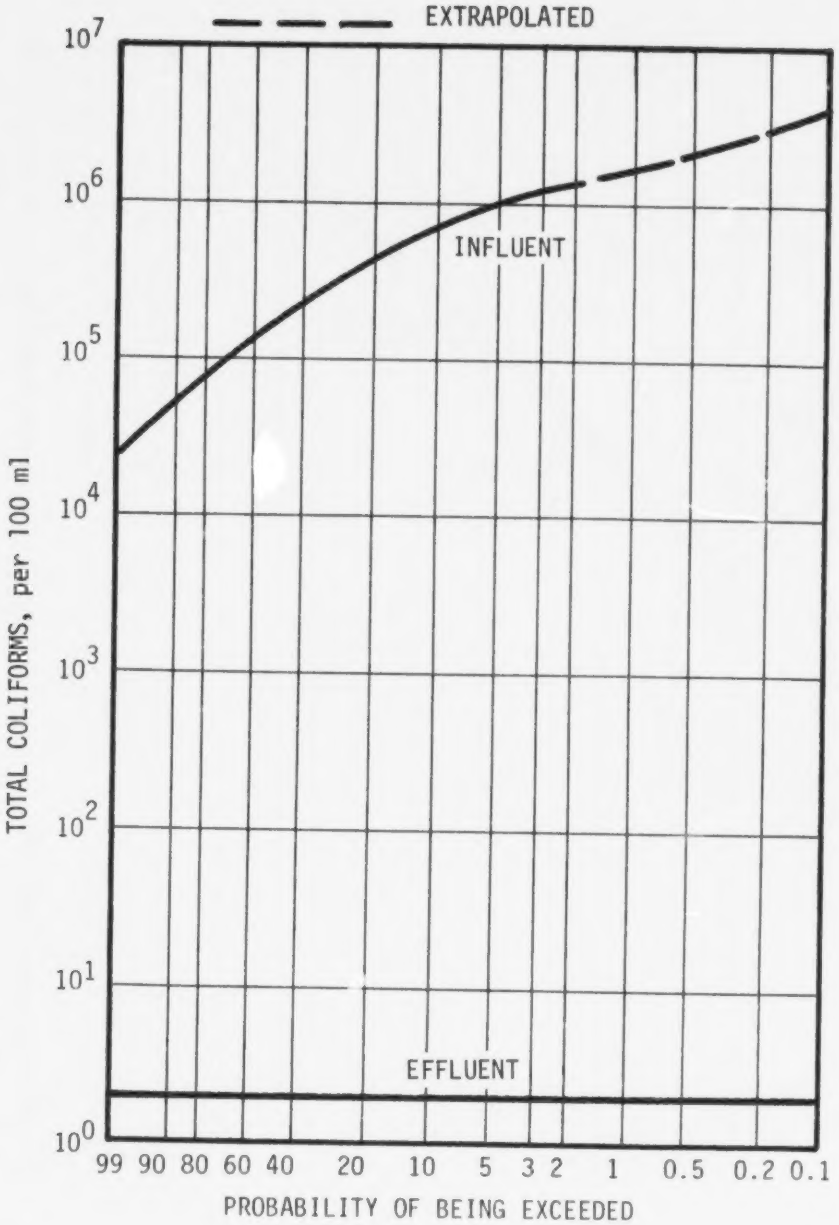


Figure 73. Extreme-value frequency distribution of total coliform data for Run No. U3.

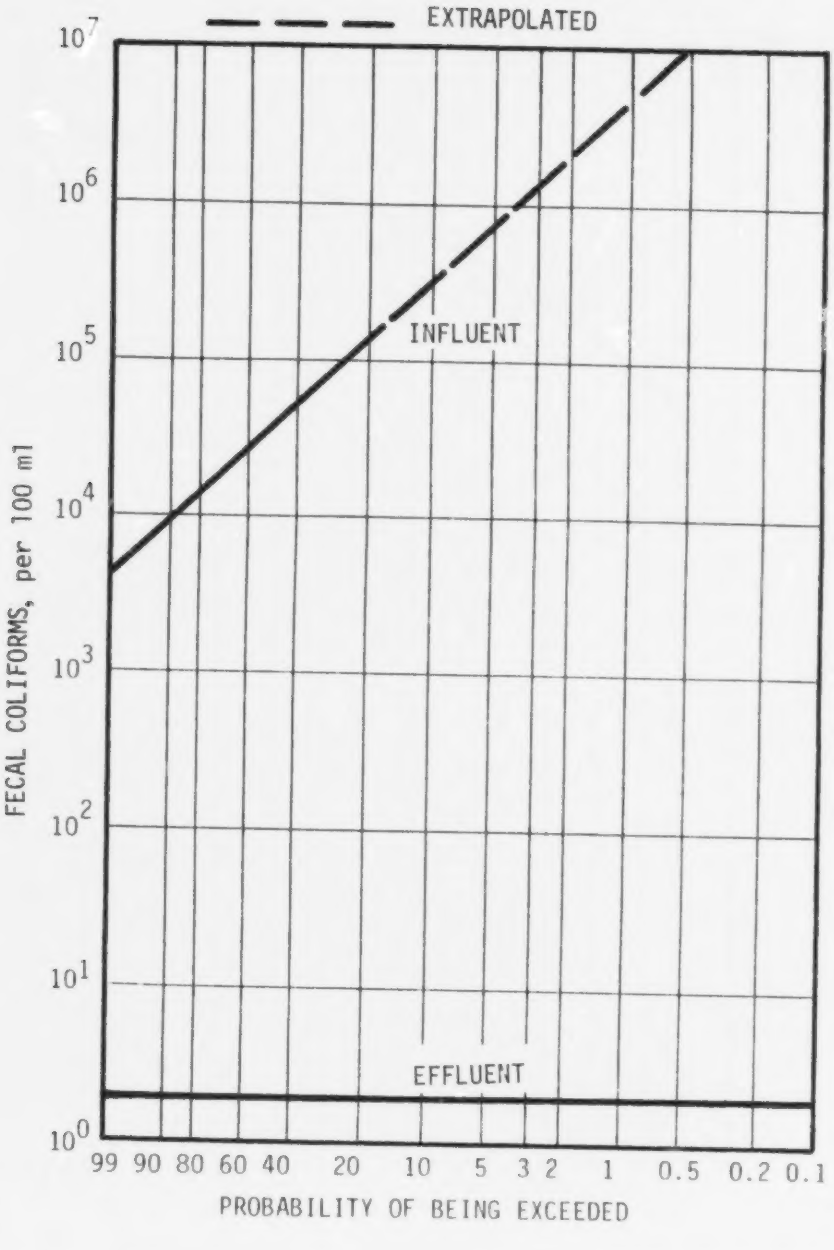


Figure 74. Extreme-value frequency distribution of fecal coliform data for Run No. U3.

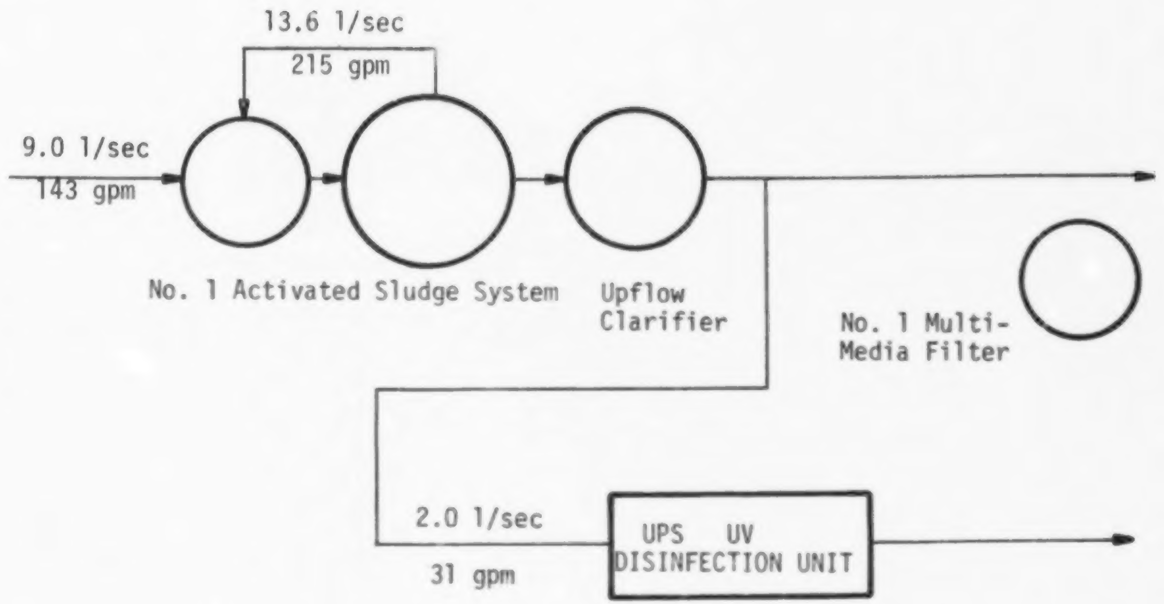

13.6 l/sec
215 gpm
9.0 l/sec
143 gpm
No. 1 Activated Sludge System
Upflow
Clarifier
No. 1 Multi-
Media Filter
2.0 l/sec
31 gpm
UPS UV
DISINFECTION UNIT

Figure 75. Pilot Plant configuration for Run No. U4, March 6 & 7, 1975.

During this run the UPS unit was operated at a mean flow rate of 1.95 liters/sec (31 gpm) which resulted in a theoretical residence time of 27.5 seconds and an actual residence time of 24.5 seconds. The mean transmittance measured at 254 nm was 66.2 percent, which corresponds to an extinction coefficient of 0.42 cm^{-1}. The calculated dose, D_T, was 25,900 μwatt-sec/cm^2. The average of the intensities measured with the radiometer was 110 μwatt/cm^2, which is equal to 980 μwatts/cm^2 at the quartz window in the exposure chamber wall after correction for geometry. The indicated dose, D_I, was 24,000 μwatt-sec/cm^2.

Since this run lasted only two days the data shown in Table 23 are very limited, but it is clear that the activated sludge process was achieving excellent nitrification and producing a good effluent. Table 24 summarizes the water quality data from the microbiological samples.

The observed log reductions were not as high as in previous runs; however, the bacterial densities in the chemically treated effluent entering the UV unit were lower than in previous configurations.

The extreme-value frequency distributions are shown in Figures 76, 77, and 78.

RUN NO. U5

Run No. U5 was one of the longest runs of the project, and during this effort the activated sludge effluent was pumped directly to the UPS UV unit as shown in Figure 79. This run was initiated on 8 March 1975, and terminated on 14 July 1975. The average flow rate through the UPS unit was 2.5 l/sec (39 gpm).

Water quality data for the No. 1 activated sludge system are presented in Table 25. It is apparent that effluent quality was lower than in previous periods. Effluent TSS averaged 29 mg/l, and the effluent COD increased to an average of 54 mg/l. Nitrification was only achieved intermittently, resulting in an average effluent ammonia nitrogen concentration of 7.1 mg/l.

The major factor responsible for the decrease in effluent quality was mechanical failure of the mixing and oxygen transfer equipment in the No. 1 aeration basin, which occurred in early April. From that time until mid-July temporary air diffusers were used, and the diffusers were, at best, of marginal utility. The result was the operation of the system with very limited oxygen transfer capability.

During Run U5 the average flow of 2.5 liters/sec resulted in a theoretical residence time of 21.4 seconds and an actual residence time of 19.5 seconds. The mean transmittance value measured at 254 nm was 68.4 percent, which corresponds to an extinction coefficient, k, of 0.39 cm^{-1}. The average radiometer reading obtained during this run was 71 μwatts/cm^2, which results in an indicated dose, D_I, of 12,300 μwatt-sec/cm^2 after correction for system geometry and multiplication by the actual residence time.

TABLE 23. PERFORMANCE OF THE NO. 1 ACTIVATED SLUDGE SYSTEM AND UPFLOW CLARIFIER DURING RUN NO. U4

Parameter	A. S. Inf. mg/l	A. S. Eff. mg/l	Upflow Clarifier Effluent mg/l	Removal percent
TSS	96	14	22	77
TOC,(soluble)	56	14	12	79
NH_3-N	19	0.2	0.8	96
Org-N	10.3	2.3	1.7	83

TABLE 24. RESULTS OF RUN U4

	Influent					Effluent					
Parameter	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow, l/sec	4	1.64	2.20	1.95	-	-	-	-	-	-	-
Turbidity,NTU	4	2.6	3.6	2.0	-	4	2.4	4.0	3.0	-	-
TSS, mg/l	4	2	12	6	-	4	2	15	7	-	-
Color, Pt-Co Units	4	20	30	25	-	4	20	35	26	-	-
TOC, mg/l	4	4	13	9	-	4	4	11	8	-	-
COD, mg/l	2	19	19	19	-	2	19	19	19	-	-
Percent Transmittance at 254 nm	2	59.8	72.6	66.2	-	-	-	-	-	-	-
Standard Plate Count per ml	5	5.7×10^3	6.7×10^4	1.3×10^4	4.11	6	3.2×10^1	1.6×10^2	6.6×10^1	1.82	2.29
Total Coliforms per 100 ml	8	5.0×10^3	2.4×10^5	2.9×10^4	4.46	8	$<2.0 \times 10^0$	2.4×10^2	$<1.1 \times 10^1$	<1.04	>3.42
Fecal Coliforms per 100 ml	8	2.0×10^3	4.2×10^4	6.0×10^3	3.78	8	$<2.0 \times 10^0$	3.3×10^1	$<4.3 \times 10^0$	<0.63	>3.15

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

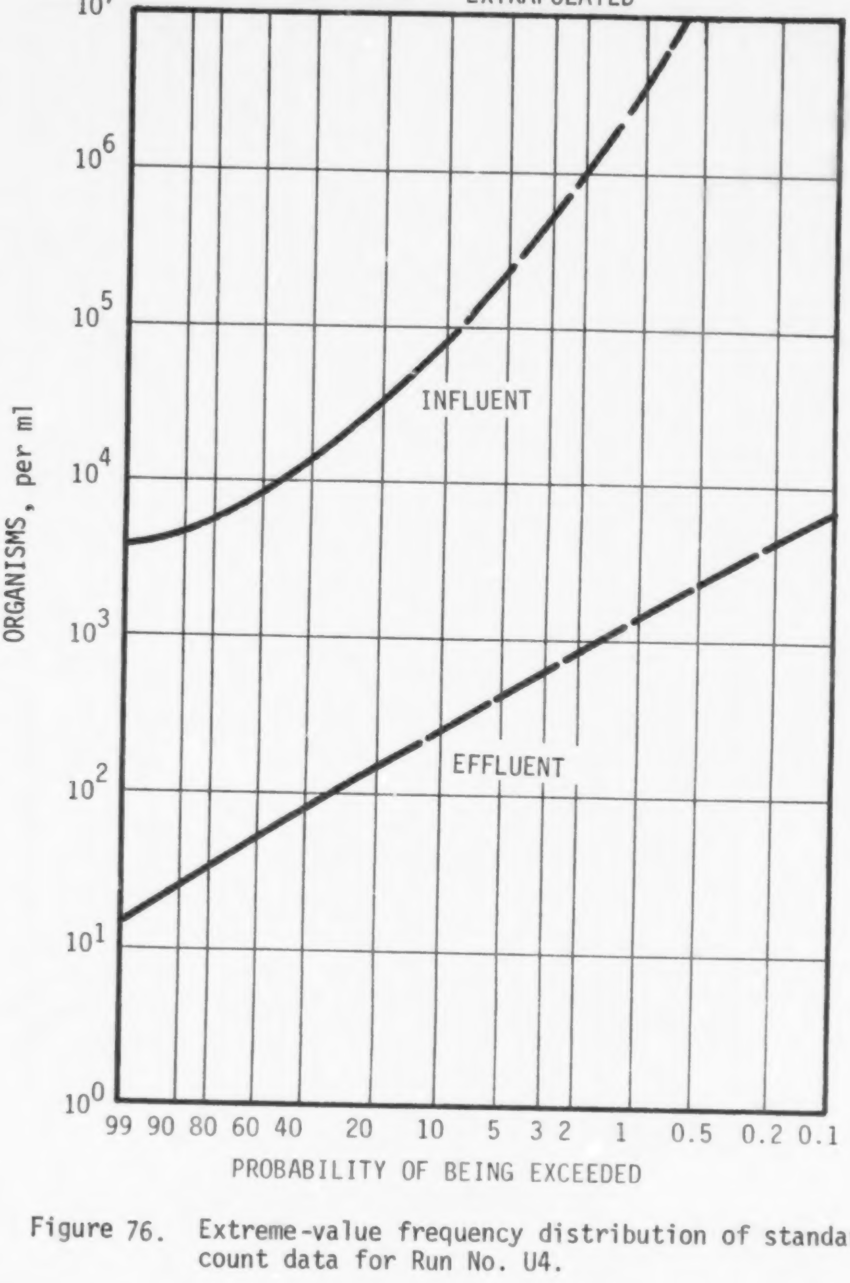


Figure 76. Extreme-value frequency distribution of standard plate count data for Run No. U4.

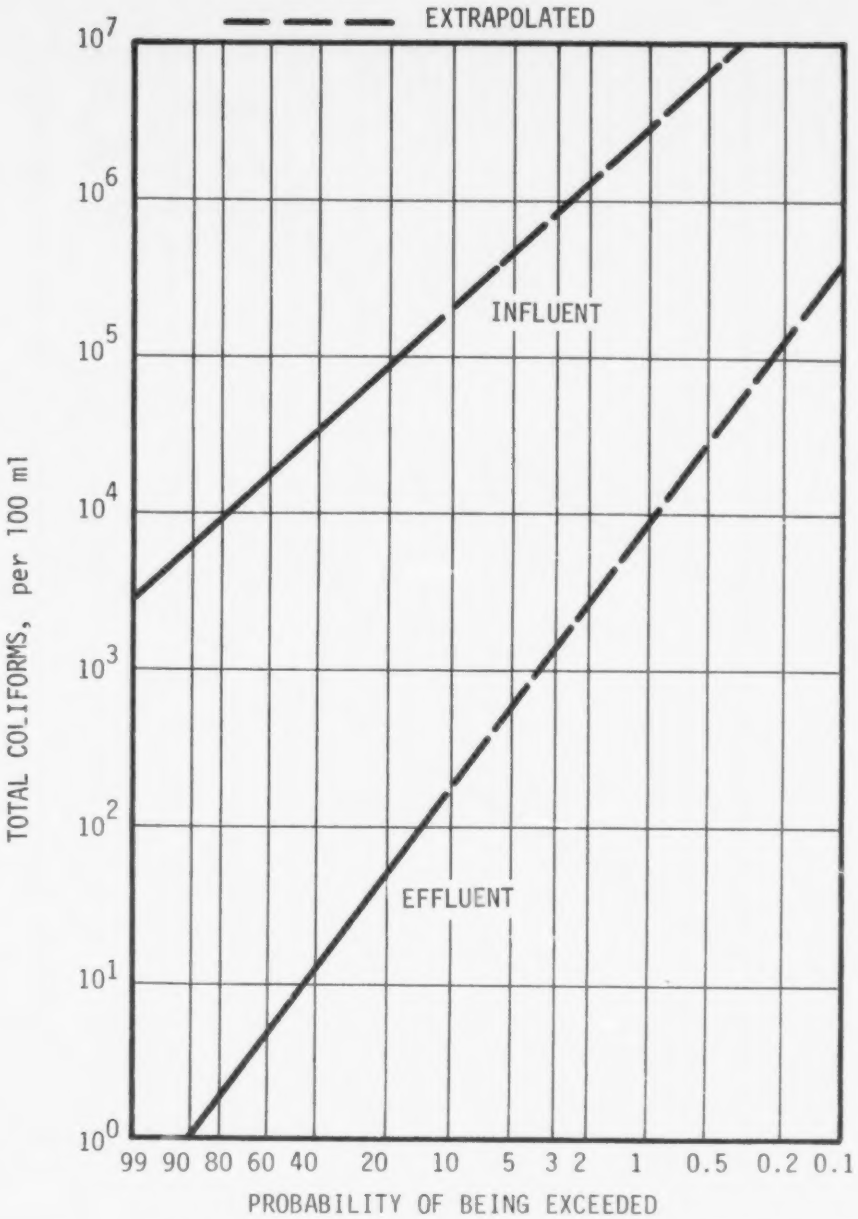


Figure 77. Extreme-value frequency distribution of total coliform data for Run No. U4.

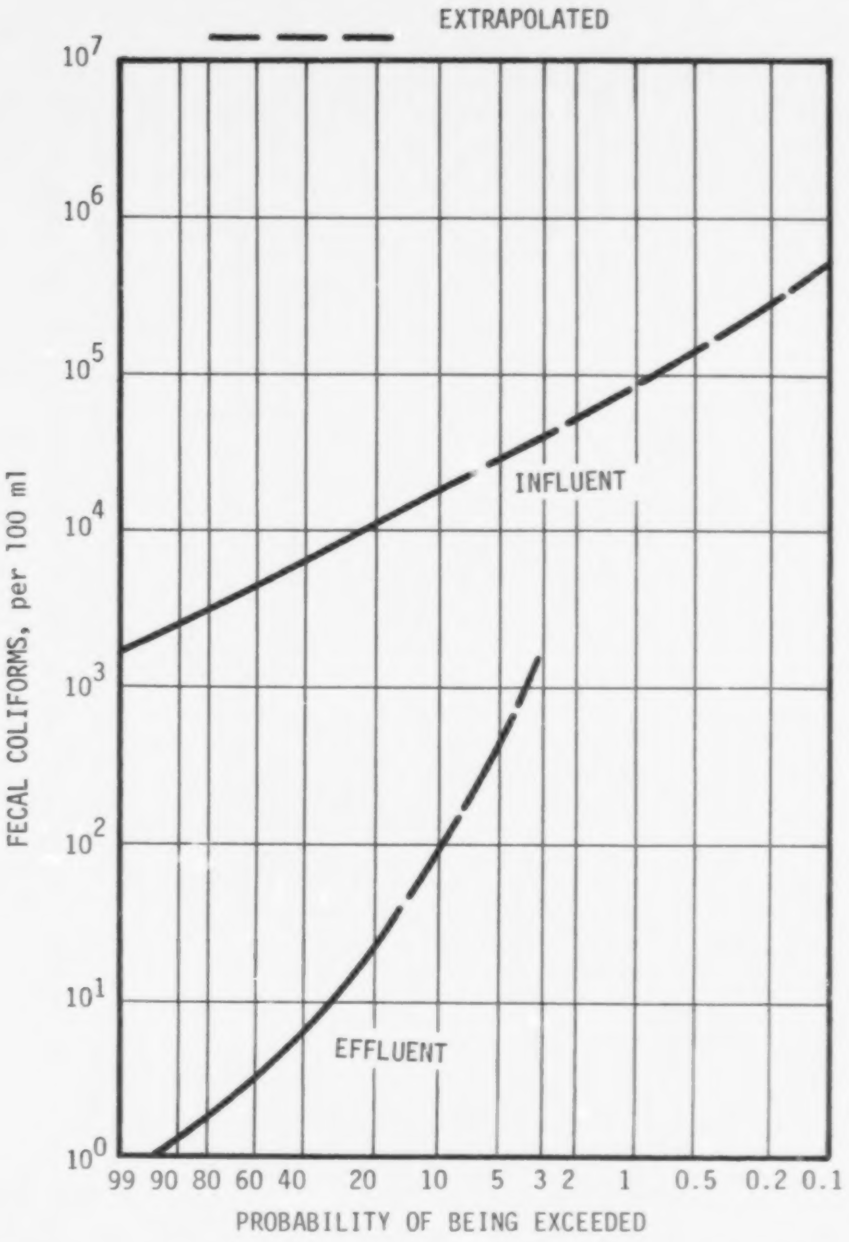


Figure 78. Extreme-value frequency distribution of fecal coliform data for Run No. U4

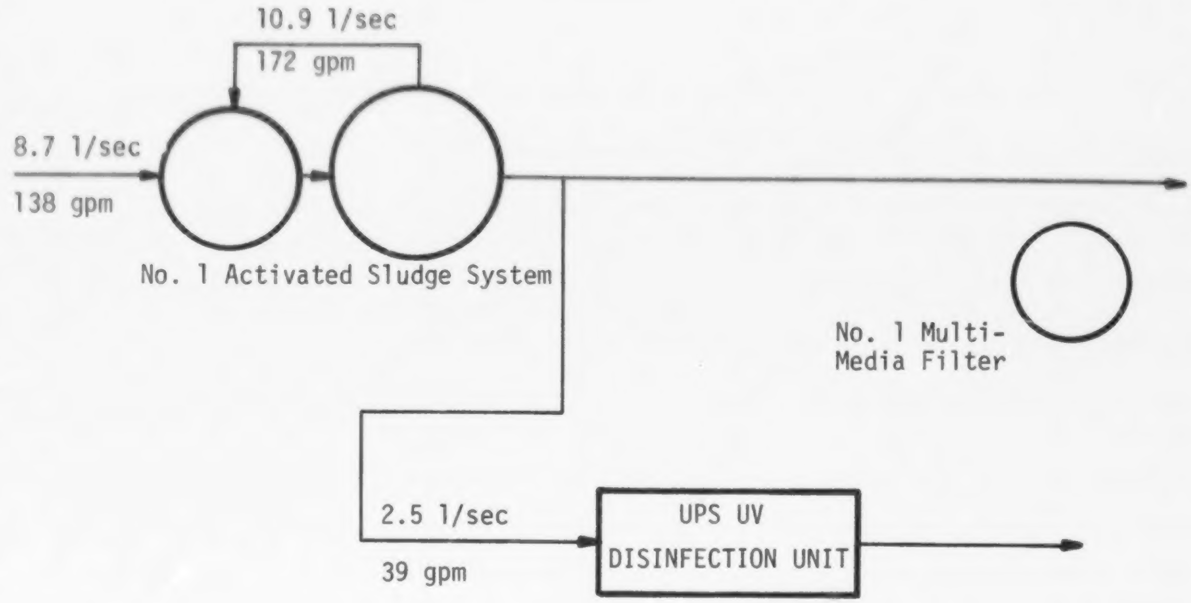

10.9 l/sec
172 gpm
8.7 l/sec
138 gpm
No. 1 Activated Sludge System
No. 1 Multi-
Media Filter
2.5 l/sec
39 gpm
UPS UV
DISINFECTION UNIT

Figure 79. Pilot Plant configuration for Run U5; March 8 to July 14, 1975.

TABLE 25. PERFORMANCE OF THE NO. 1 ACTIVATED SLUDGE SYSTEM DURING RUN NO. U5

Parameter	Influent mg/l	Effluent mg/l	Removal percent
TSS	84	29	65
BOD_5	91	24	74
COD	229	54	77
TOC,soluble	42.5	13.0	69
NH_3-N	16.6	7.1	57
Org-N	8.4	4.0	52
NO_2 & NO_3-N	0.26	2.4	-
Total N	25.3	13.5	47
Total P	7.5	5.8	23
Turbidity, NTU	4.8	4.8	0

The data from the microbiological grab samples are summarized in Table 26. The total and fecal coliform reductions were not as high as in previous runs.

The time series plot of the standard plate counts, Figure 80, indicates a sudden increase in influent and effluent counts during early April. Total coliform densities also increased sharply in April (Figure 81), followed by gradual increases in late June and early July. The same trends were noted in the fecal coliform data (Figure 82). Included in Figure 82 is a time-series plot of NH_3-N concentrations. It is evident that changes in NH_3-N concentrations were paralleled by corresponding changes in fecal coliform numbers during this period.

Figures 83 and 84 are plots of the UV intensity measured by the IL 500 radiometer (at the quartz window) and observed log reductions in total coliforms and fecal coliforms, respectively. Good correlations exist, which one would expect since the measured intensity and the actual dose are related. The relationship between the intensity measured with the IL 500 and the indicated dose, D_I, has been previously discussed. Several factors can be responsible for the variations noted in the measured UV intensity, but changes in transmissability at 254 nm and slime accumulation on the quartz sleeves surrounding the UV lamps are probably the most significant variables. Both of these factors are discussed in Section 9 of this report.

The estimating equations and correlation coefficients for total and fecal coliform densities and measured UV intensity are presented on Figures 83 and 84, respectively.

Figures 85, 86, and 87 are the extreme value frequency distributions for Run No. U5. The fecal coliform data indicate that 280 organisms per 100 ml could be expected 50 percent of the time, worse than in any previous run. Additionally, the log reductions of organisms observed during this run were not as good as in previous runs.

The decrease in disinfection efficiency observed during this run can be attributed to a number of different factors. The operational difficulties with the activated sludge system resulted in the production of an effluent of lower quality that was somewhat more difficult to disinfect. The effluent transmissability at 254 nm was lower than in all previous runs and the influent organism densities were higher than in all previous runs, as were the mean UV influent COD and ammonia-N concentrations.

Furthermore, the flow to the UPS unit was intentionally increased to stress the disinfection capability of the system. The result was a calculated dose, D_I, that was approximately 40 percent lower than in all previous runs. In addition the measured mean UV intensity (uncorrected) of 71 μwatt/cm^2 was substantially lower than the 137, 220, and 110 μwatts/cm^2 measured during runs U2, U3, and U4, respectively.

TABLE 26. RESULTS OF RUN U5

	Influent					Effluent					
Parameter	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean log Reduction[2]
Flow, l/sec	97	1.58	4.66	2.46	-	-	-	-	-	-	-
Turbidity,NTU	62	1.5	27	4.8	-	61	1.8	18	5.3	-	-
TSS, mg/l	97	2	282	27	-	97	2	280	24	-	-
Color, Pt-Co Units	97	20	>70	>49	-	97	20	>70	>46	-	-
TOC, mg/l	88	4	20	11	-	87	4	21	10	-	-
COD, mg/l	94	14	190	44	-	94	11	203	43	-	-
Percent Transmittance at 254 nm	48	47.9	76.7	68.4	-	-	-	-	-	-	-
Standard Plate Count per ml	77	7.6x10^{3}	3.0x10^{7}	1.5x10^{5}	5.18	80	3.0x10^{1}	5.2x10^{4}	3.0x10^{2}	2.48	2.70
Total Coliforms per 100 ml	192	4.9x10^{4}	>2.4x10^{8}	>9.0x10^{5}	>5.95	194	1.1x10^{1}	>2.4x10^{5}	>7.8x10^{2}	>2.89	3.06
Fecal Coliforms per 100 ml	192	4.9x10^{4}	2.4x10^{8}	>2.9x10^{5}	>5.46	192	>2.0x10^{0}	>2.4x10^{5}	>2.8x10^{2}	>2.45	3.01

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

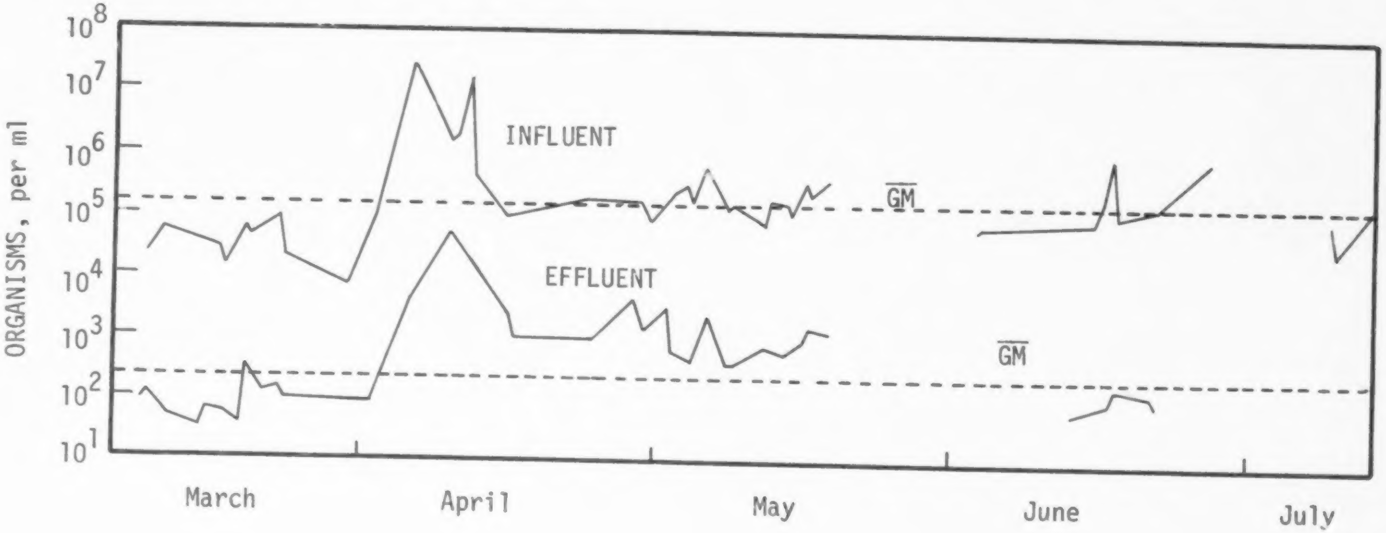


Figure 80. Standard plate count data for Run No. U5.

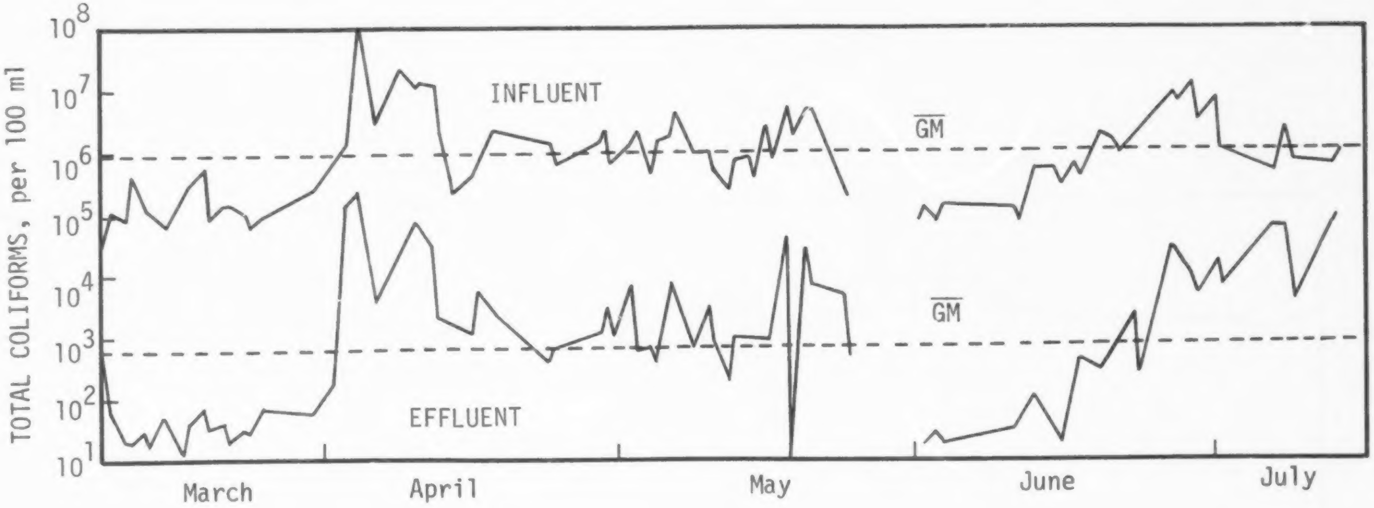


Figure 81. Total coliform data for Run No. U5.

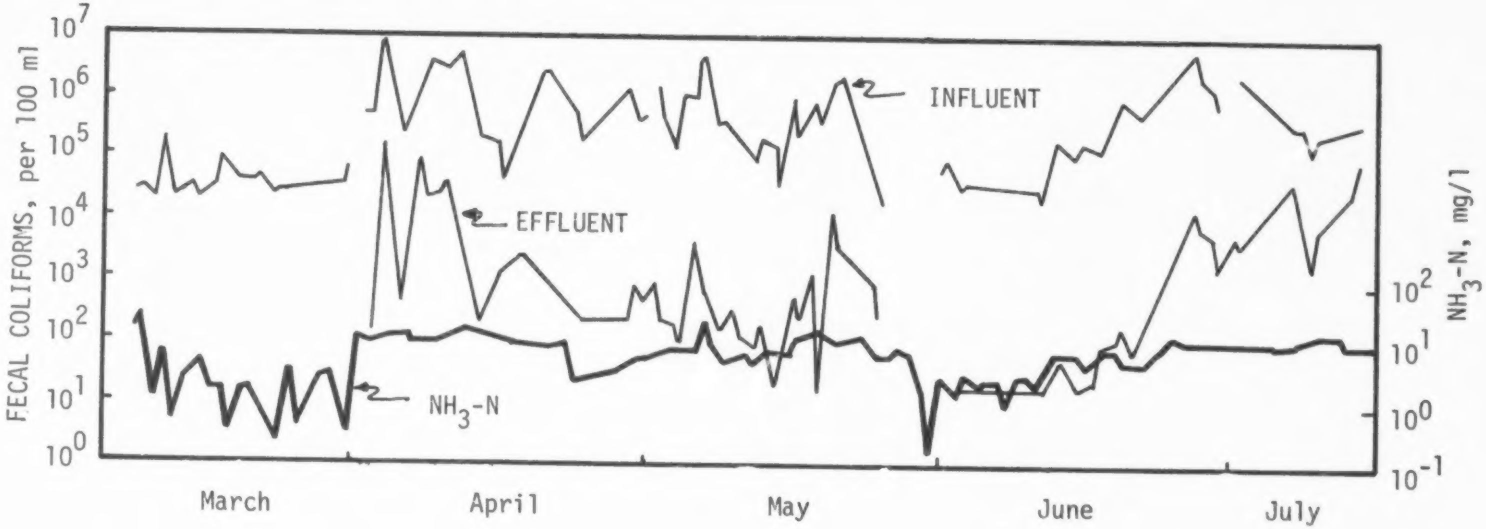


Figure 82. Fecal coliform data for Run No. U5.

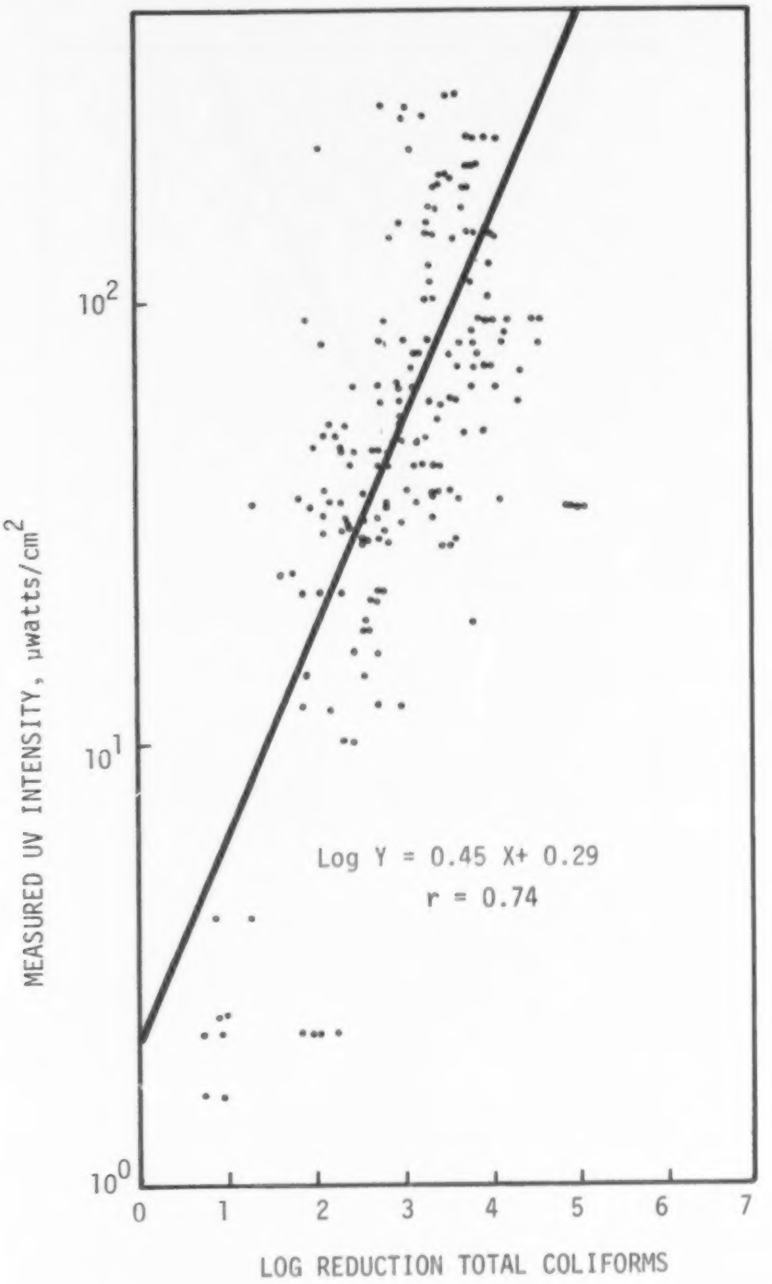


Figure 83. UV intensity versus log reduction of total coliforms for Run No. U5.

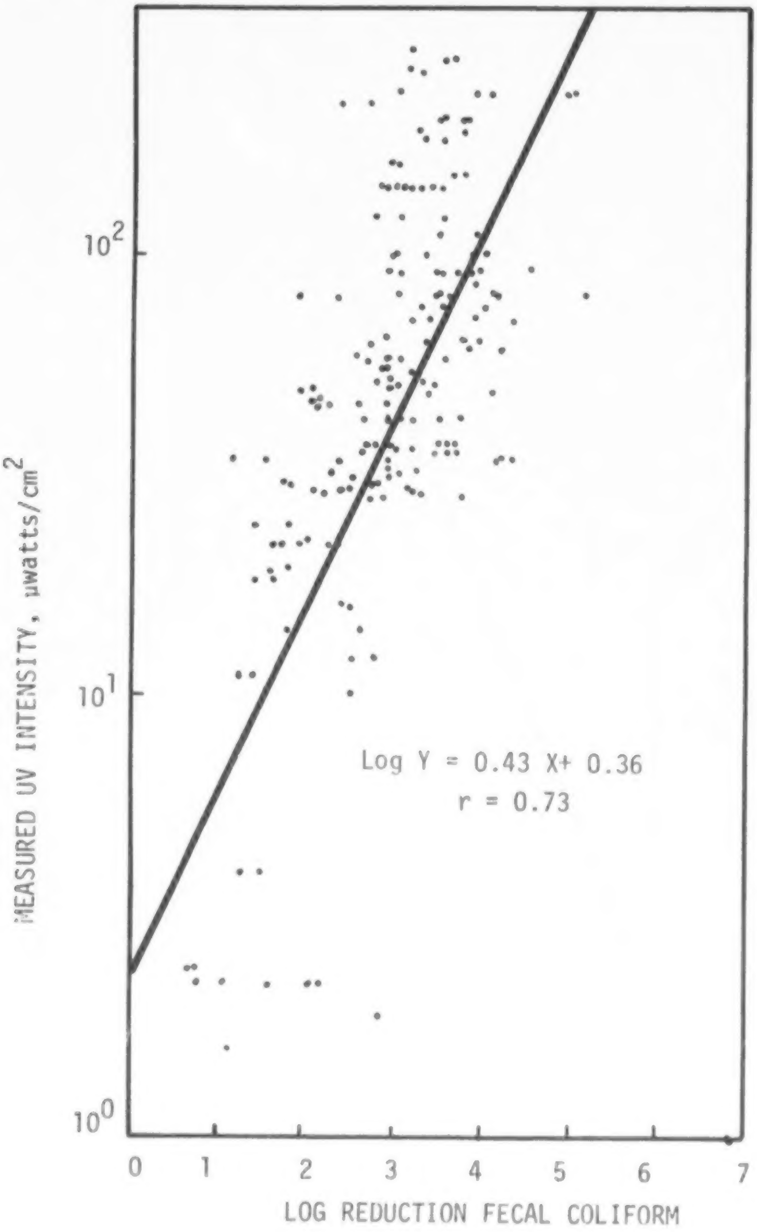


Figure 84. UV intensity versus log reduction of fecal coliforms for Run No. U5.

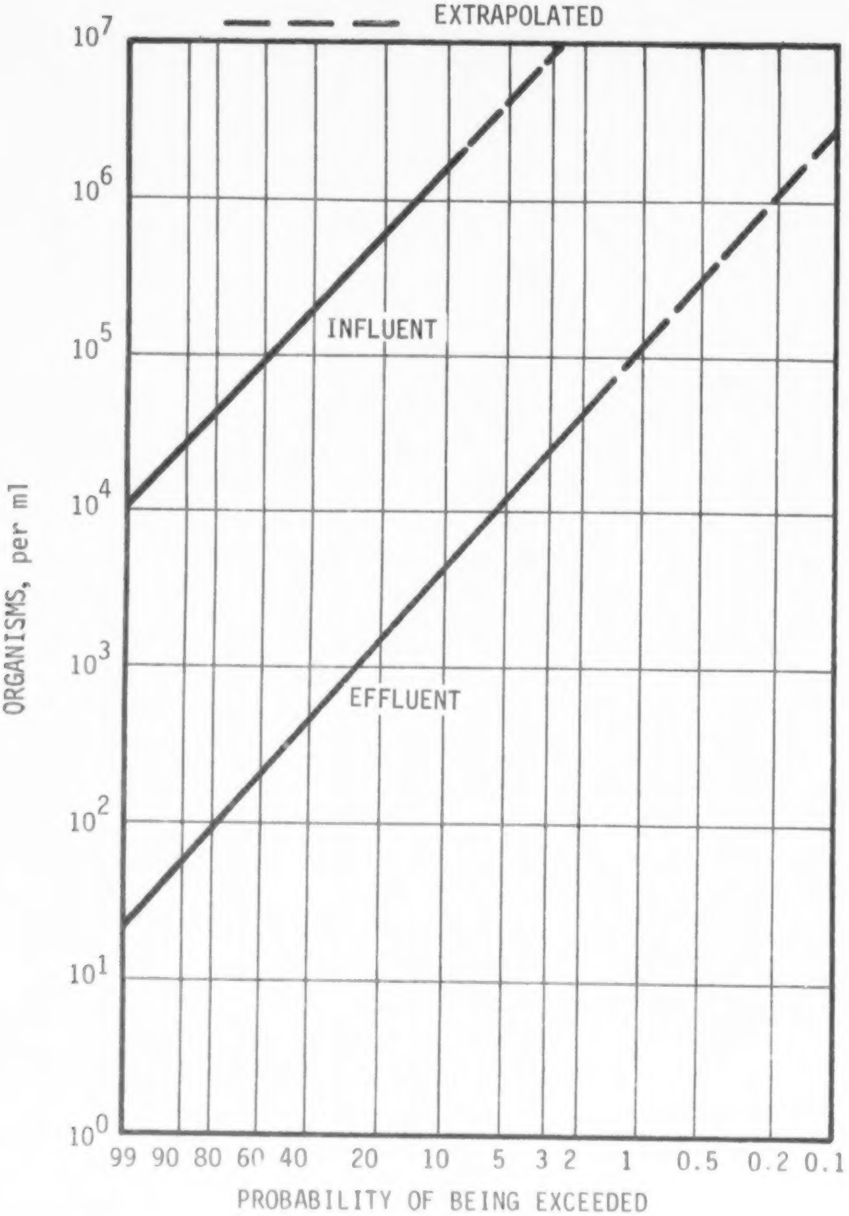


Figure 85. Extreme-value frequency distribution of standard plate count for Run No. U5.

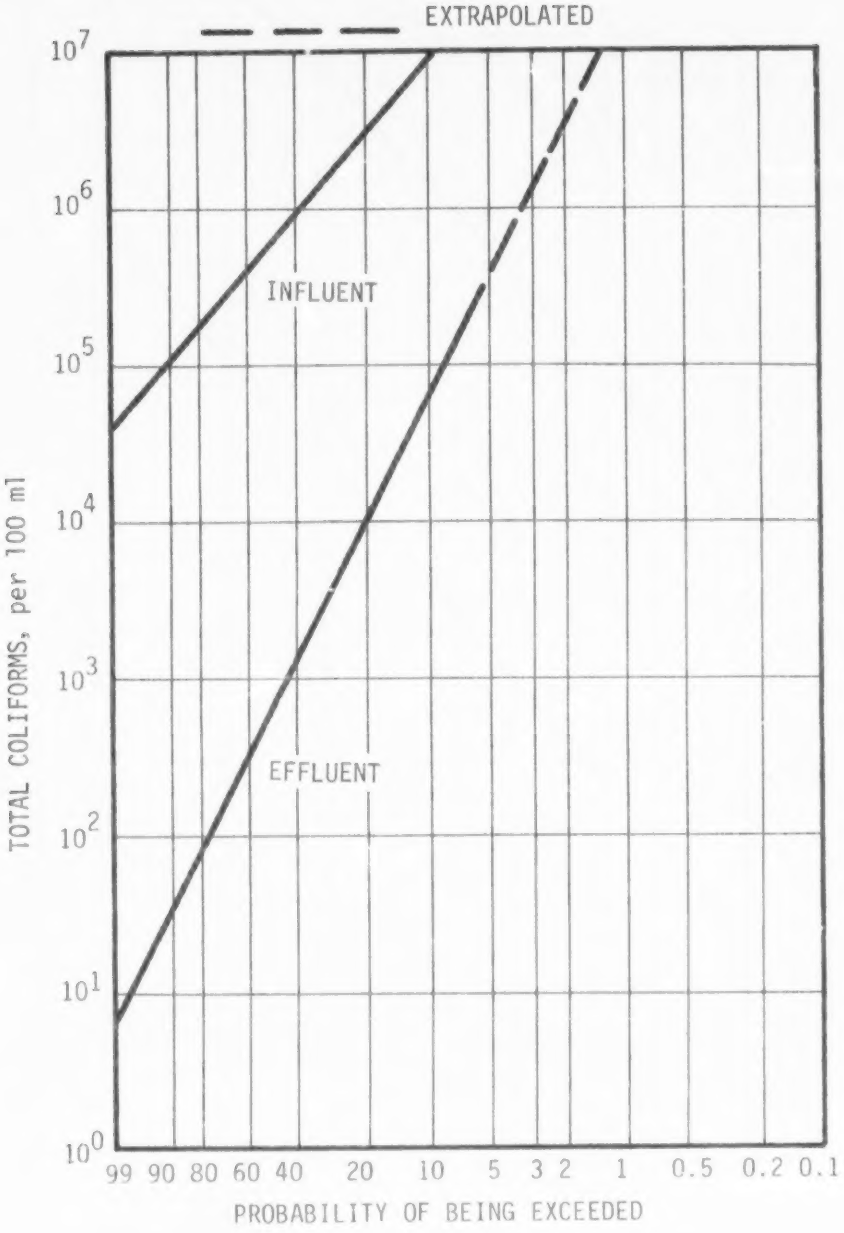


Figure 86. Extreme-value frequency distribution of total coliform data for Run No. U5.

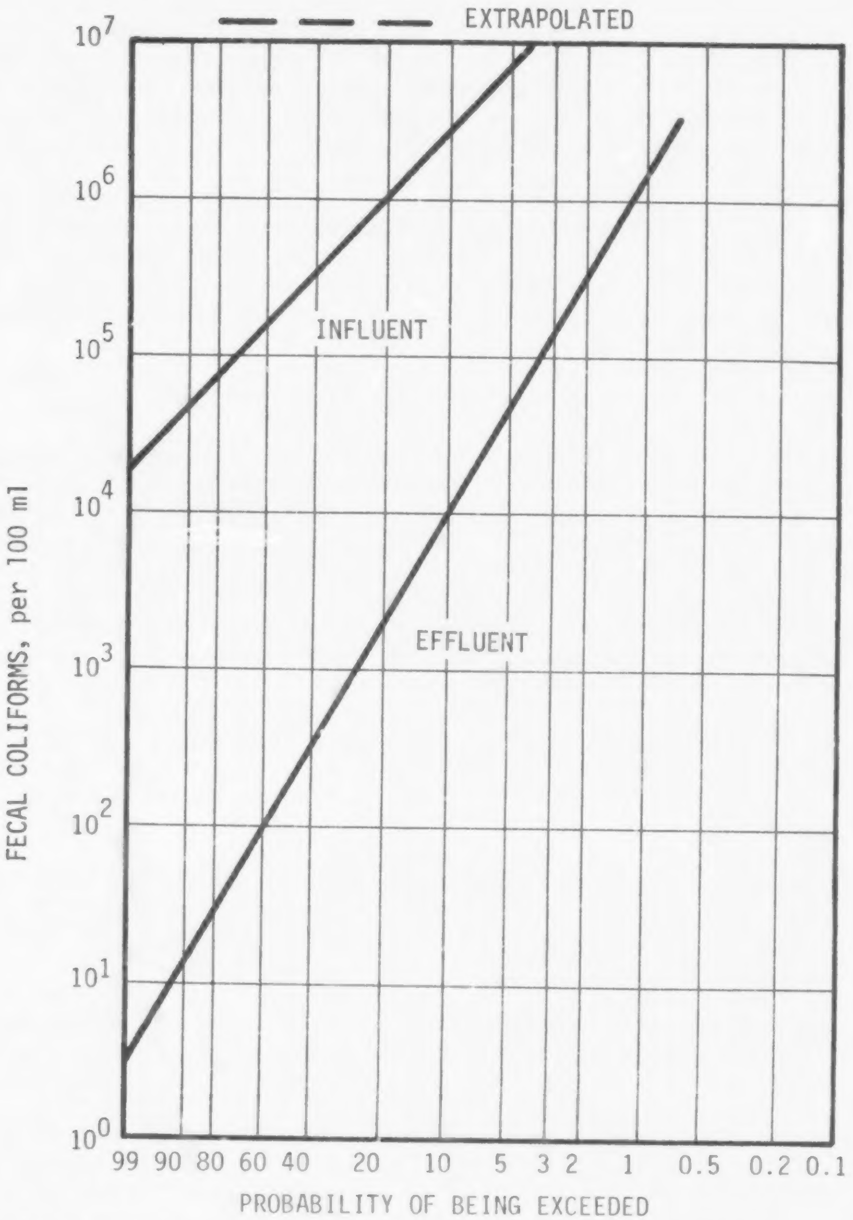


Figure 87. Extreme-value frequency distribution of fecal coliform data for Run No. U5.

RUN NO. U6

Run No. U6 was conducted on filtered activated sludge effluent from 15 July to 3 August 1975, as indicated in Figure 88. The water quality data for this run are summarized in Table 27. It is clear that effluent quality was poor, due to the absence of adequate oxygen transfer capacity in the No. 1 activated sludge system. This deterioration in effluent quality caused a marked reduction in UV disinfection efficiency.

The gross organic water quality parameters presented in Tables 27 and 28 indicate clearly the poor quality of the effluent that was being produced by the activated sludge process. Filtered COD and BOD_5 concentrations averaged 69 and 18 mg/l, respectively, and under normal conditions a COD and BOD of 25 and 5 would have been anticipated. Effluent color averaged >48 Pt-Co units,as compared to previous values of 25. The high TSS concentrations in the filtered effluent are the result of insufficient backwash water flow, and thus, incorrectly backwashed filters.

During this run the filtered activated sludge effluent was pumped to the UPS UV unit at an average flow rate of 2.2 liters/sec (35 gpm), which resulted in a theoretical residence time of 24.4 seconds and an actual residence time of 22.0 seconds. The effect of reduced effluent quality on UV transmissibility was clearly evident. During this run the average extinction coefficient, k, was 0.61 cm^{-1}, which corresponds to 54.1 percent transmittance. In all previous runs the transmittance ranged from 66 to 72 percent. The calculated dose, D_T, was the lowest observed during the project, and averaged 10,800 μwatt-sec/cm^2.

The mean intensity value measured with the IL500 was 39 μwatts/cm^2. The average for the four previous runs was 135 μwatts/cm^2, 246 percent higher than the value measured for this run. The indicated dose, D_I, for Run U6 was only 7640 μwatt-sec/cm^2.

Microbiological data are summarized in Table 28. During this run the geometric mean fecal coliform density was greater than 2000 per 100 ml, which was two to three logs higher than previous runs when there was adequate oxygen transfer capacity.

The mean log reduction in fecal and total coliform organisms averaged 2.69 and 2.74, respectively, while the mean standard plate count reduction was 2.42 logs.

Figures 89, 90, and 91 are time series plots of the microbiological data. The large decrease in effluent counts on July 23 coincided with the cleaning of the unit on that date. The very significant variation in effluent bacterial densities are important if one must achieve consistently good disinfection.

Figures 92 and 93 are plots of the UV intensity measured by the IL 500 radiometer (at the quartz window) and observed log reduction in total coliforms and fecal coliforms, respectively. Again, good correlations

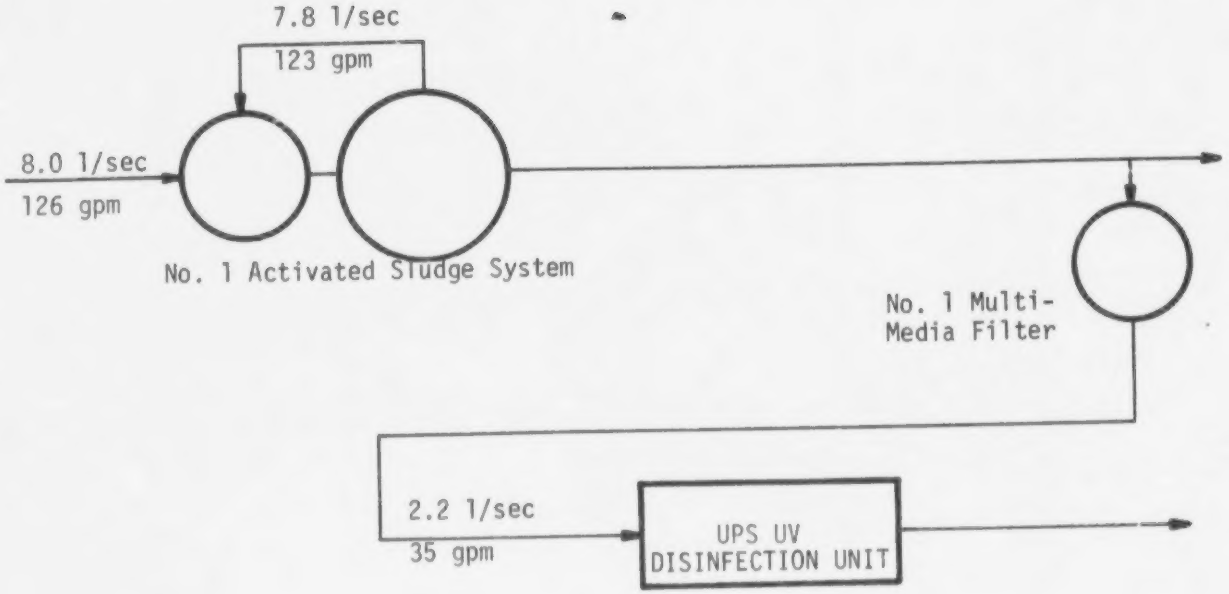

7.8 l/sec
123 gpm
8.0 l/sec
126 gpm
No. 1 Activated Sludge System
No. 1 Multi-
Media Filter
2.2 l/sec
35 gpm
UPS UV
DISINFECTION UNIT

Figure 88. Pilot Plant configuration for Run No. U6; July 15 to August 3, 1975.

TABLE 27. PERFORMANCE OF THE ACTIVATED SLUDGE SYSTEM AND MULTIMEDIA FILTERS DURING RUN NO. U6

Parameter	A.S. Influent mg/l	A.S. Effluent mg/l	Filter No. 1 Effluent	Removal percent
TSS	78	58	30	62
BOD_5	119	31	18	93
COD	239	107	69	71
TOC, soluble	52.8	21.2	19.6	63
NH_3-N	15.7	12.8	12.6	20
Org-N	8.1	6.7	5.2	36
NO_2 & NO_3-N	0.2	0.3	0.2	-
Total N	24.0	19.8	18.0	25
Total P	9.3	6.7	7.3	22
Turbidity, NTU	-	4.7	4.6	-
Color, Pt-Co units	-	46	48	-

TABLE 28. RESULTS OF RUN U6.

	Influent					Effluent					
Parameter	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean log Reduction[2]
Flow, l/sec	35	1.58	2.65	2.20	-	-	-	-	-	-	-
Turbidity,NTU	29	1.0	16	4.9	-	29	0.8	10	4.6	-	-
TSS, mg/l	36	2	83	19	-	36	3	69	18	-	-
Color, Pt-Co Units	37	20	>70	>48	-	37	20	>70	>48	-	-
TOC, mg/l	26	9	27	17	-	26	9	26	17	-	-
COD, mg/l	35	17	122	55	-	35	17	99	51	-	-
Percent Transmittance at 254 nm	28	26	72	54	-	-	-	-	-	-	-
Standard Plate Count per ml	17	$1.1x10^5$	$2.5x10^6$	$4.2x10^5$	5.62	12	$1.6x10^2$	$1.1x10^5$	$1.6x10^3$	3.20	2.42
Total Coliforms per 100 ml	46	$<2.0x10^5$	$4.6x10^7$	$<2.2x10^6$	<6.34	46	$<2.0x10^1$	$9.2x10^5$	$<4.0x10^3$	<3.60	2.74
Fecal Coliforms per 100 ml	49	$1.7x10^5$	$1.1x10^7$	$9.8x10^5$	5.99	48	$<2.0x10^1$	$3.5x10^5$	$<2.0x10^3$	<3.30	>2.69

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

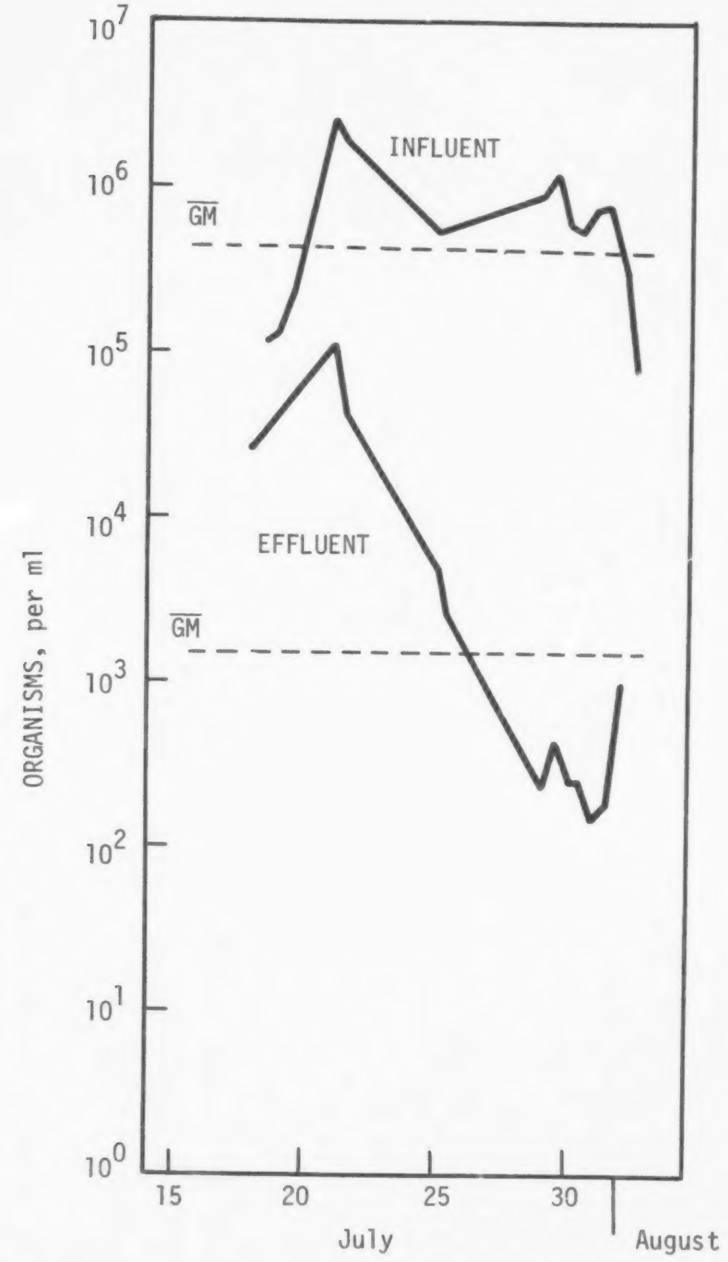


Figure 89. Standard plate count data for Run No. U6.

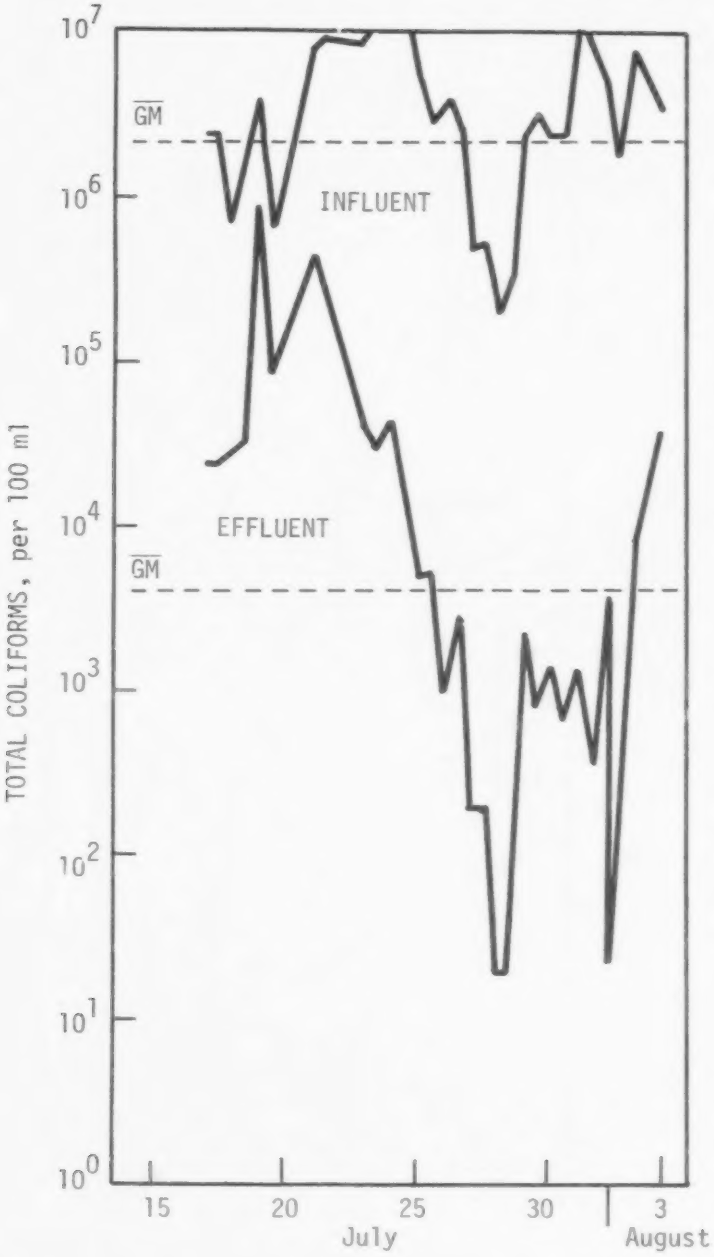


Figure 90. Total coliform data for Run No. U6.

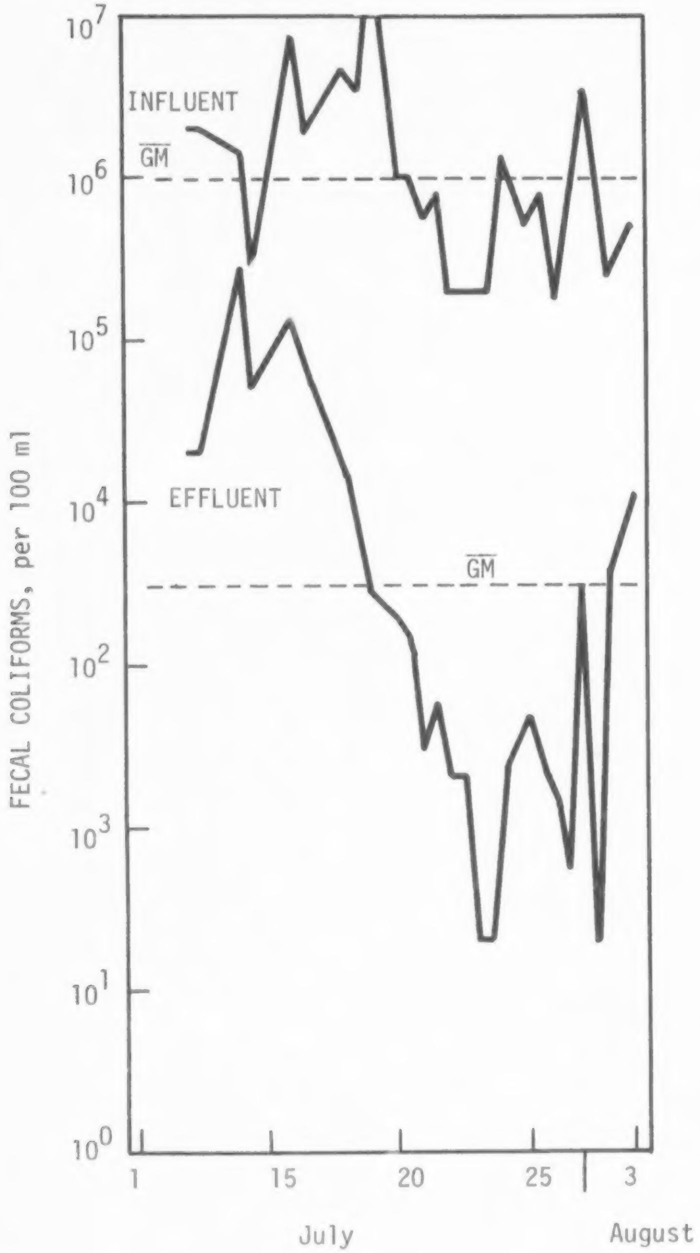


Figure 91. Fecal coliform data for Run No. U6.

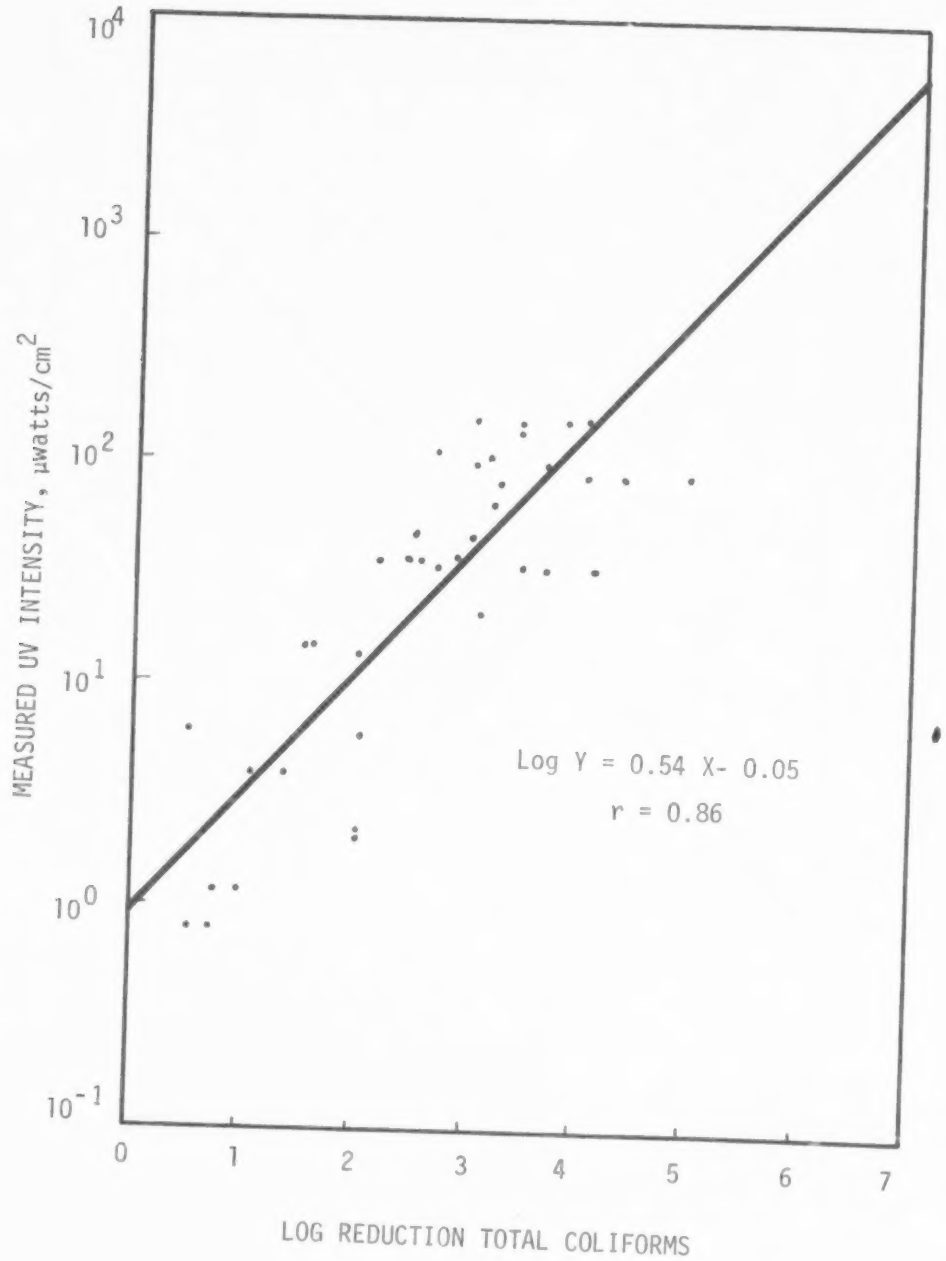


Figure 92. UV Intensity versus log reduction of total coliform data for Run No. U6.

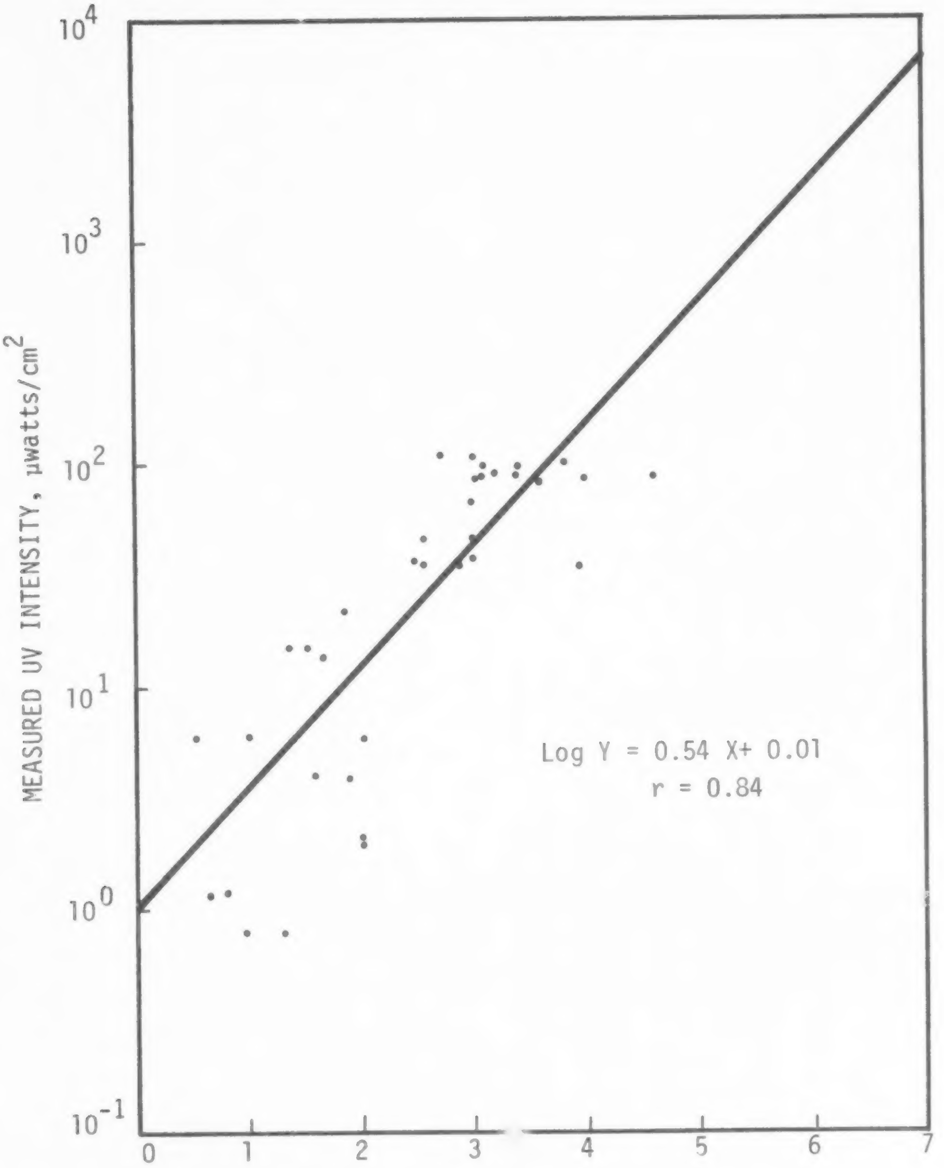


Figure 93. UV Intensity versus log reduction of fecal coliform data for Run No. U6.

existed and the estimating equations and correlation coefficients are presented on Figures 92 and 93.

Extreme-value frequency distributions for the microbiological data are shown on Figures 94, 95 and 96. A fecal coliform density of 200/100 ml would be exceeded over 70 percent of the time. Additionally, the steep slope of the effluent line is indicative of extreme variability in the data, a situation that should be expected with a poor effluent and a low UV dose.

RUN NO. U7

Run No. U7 was initiated immediately after the installation of new aeration equipment on 8 August and terminated on 5 October 1975. As shown in Figure 97 the process configuration consisted of mixed-media filtration of the activated sludge effluent followed by UV disinfection with the UPS unit.

Water quality data for the unit processes are summarized in Table 29, and indicate a substantial improvement in treatment over runs U5 and U6. Nitrification was not complete; however, the effluent ammonia nitrogen averaged only 4 mg/l, indicating much improved treatment. The BOD_5 and COD in the filter effluent averaged 3 and 35 mg/l, respectively, in contrast to the BOD_5 of 18 mg/l and the COD of 69 mg/l observed during the previous run.

The data obtained from the microbiological samples are summarized in Table 30, and reflect the general improvement in treatment. The mean color value was reduced from the greater than 48 Pt-Co units observed during Run No. U6 to 19 Pt-Co units during this run. Most importantly, the transmissability increased from 54 percent to 64 percent.

During Run No. U7 the mean flow rate to the UPS unit was 3.1 liters/sec. The resulting theoretical residence time was 17.3 seconds, and the average actual residence time was 15.5 seconds. The transmissability at 254 nm of 64.1 percent corresponded to an extinction coefficient, k, of 0.45 cm^{-1} which resulted in a calculated dose, D_T, of 14,500 μwatt-sec/cm^2.

An average intensity of 123 μwatts/cm^2 was measured with the IL 500 radiometer. When this value was multiplied by 8.9 to correct for geometry, the resulting UV intensity at the quartz window in the exposure chamber wall was 1100 μwatts/cm^2. This intensity value is 300 percent greater than that measured during the previous run when effluent quality was poor. The resulting indicated dose, D_I, was 17,000 μwatt-sec/cm^2.

It is important to note that the flow was increased from 2.2 liter/sec. in Run U6 to 3.1 liters/sec. during Run U7. This resulted in a 30-percent decrease in residence time within the exposure chamber, which should have reduced the UV dose proportionately. However, the improved effluent quality, which resulted in enhanced UV transmissability actually increased the UV dose.

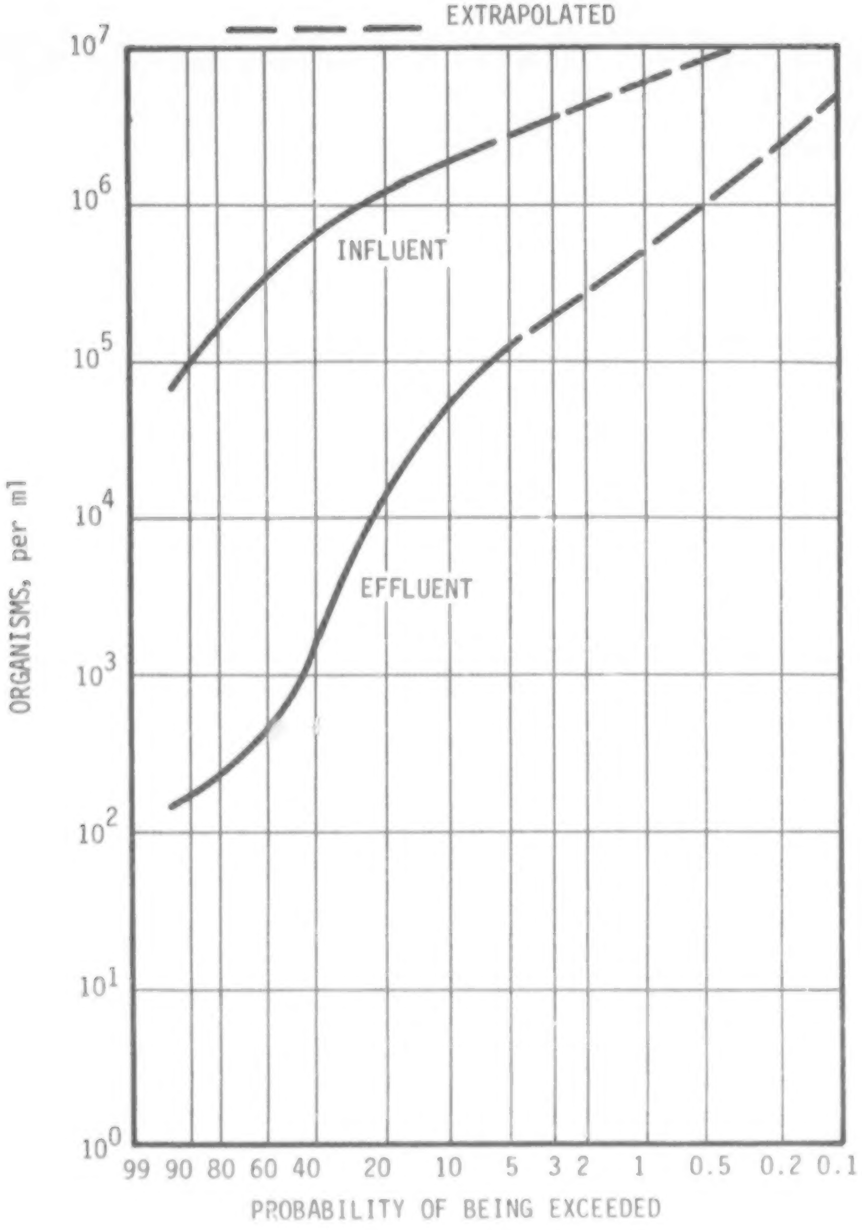


Figure 94. Extreme-value frequency distribution of standard plate count data for Run No. U6.

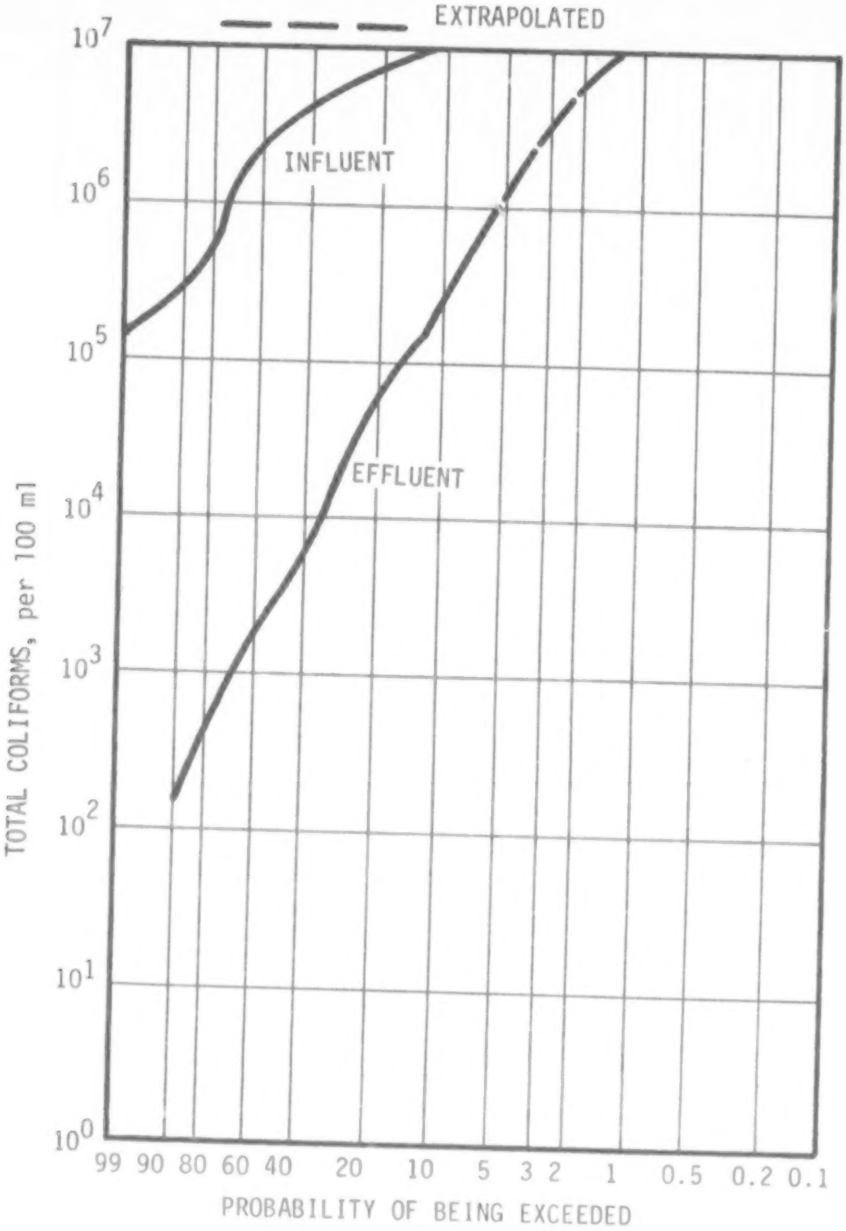


Figure 95. Extreme-value frequency distribution of total coliform data for Run No. U6.

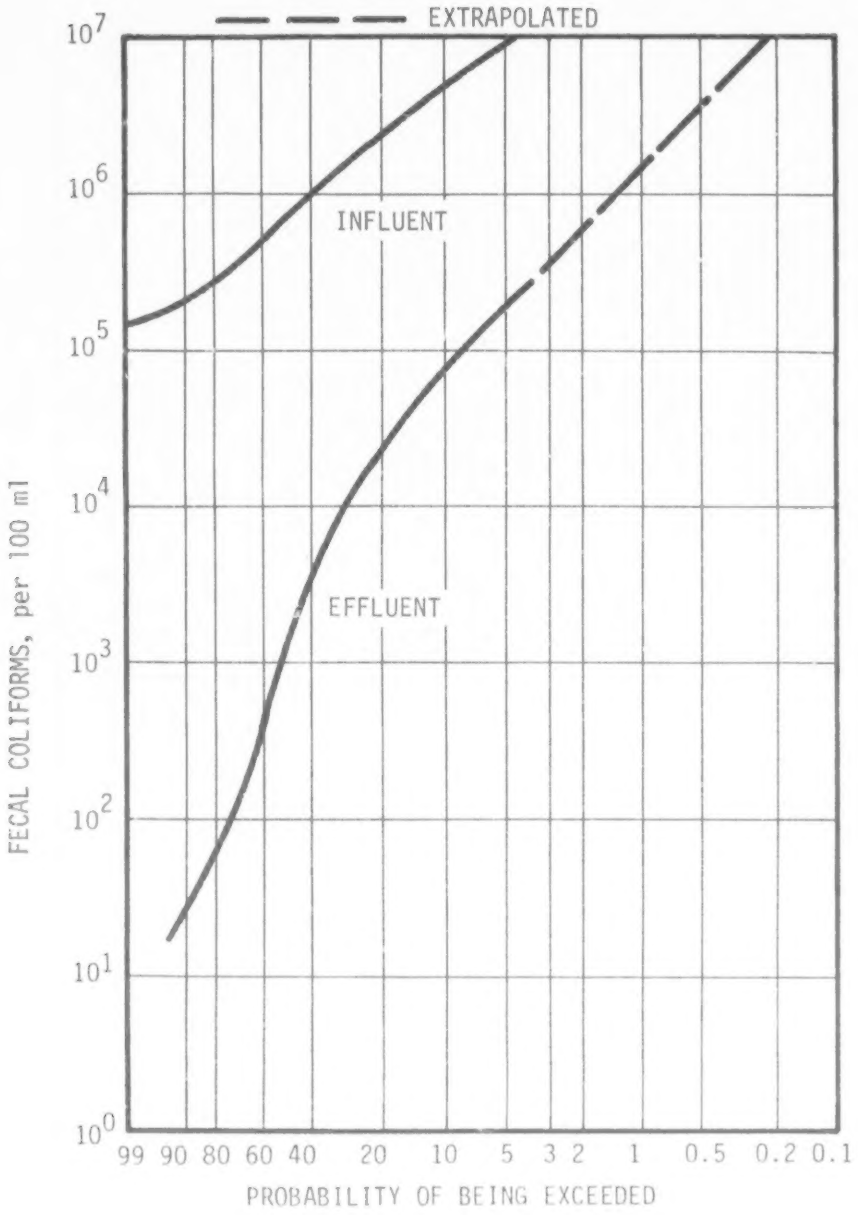


Figure 96. Extreme-value frequency distribution of fecal coliform data for Run No. U6.

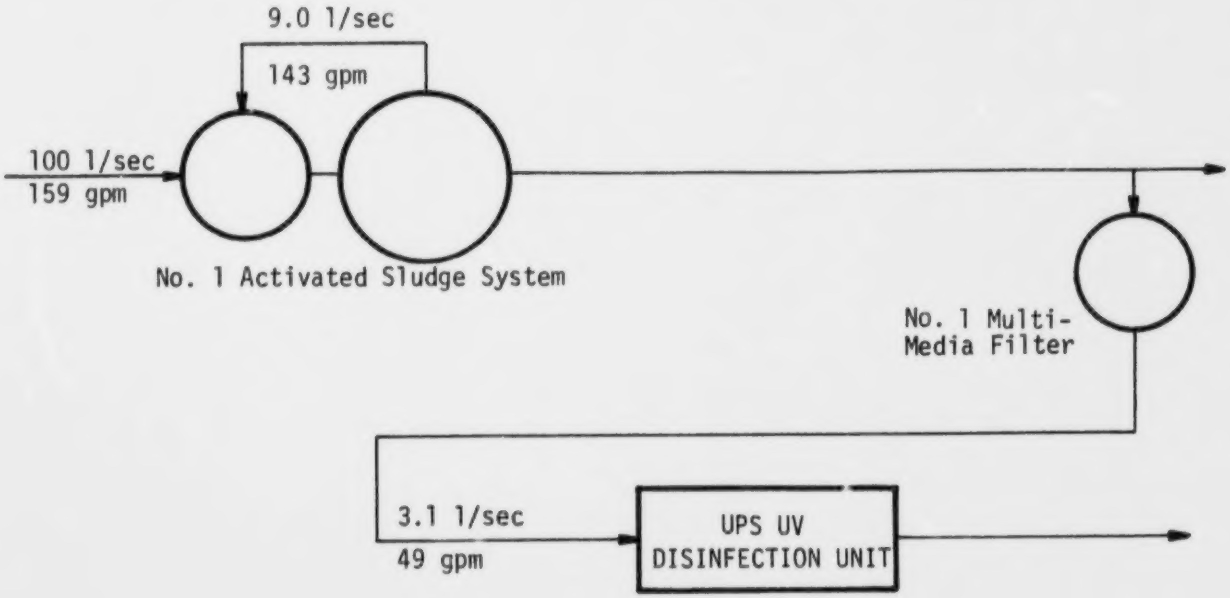

9.0 l/sec
143 gpm
100 l/sec
159 gpm
No. 1 Activated Sludge System
No. 1 Multi-
Media Filter
3.1 l/sec
49 gpm
UPS UV
DISINFECTION UNIT

Figure 97. Pilot Plant configuration for Run No. U7; August 8 to October 5, 1975.

TABLE 29. PERFORMANCE OF THE NO. 1 ACTIVATED SLUDGE SYSTEM AND MULTIMEDIA NO. 1 FILTER DURING RUN NO. U7

Parameter	A.S. Influent mg/l	A.S. Effluent mg/l	No. 1 Filter Effluent mg/l	Removal percent
TSS	83	37	23	72
BOD_5	127	9	3	98
COD/sol COD	283	61.9/30.2	35.3	88
TOC, soluble	58.3	14.3	13.8	76
NH_3-N	19.6	4.6	4.0	80
Org-N	9.7	5.0	2.8	71
NO_2&NO_3-N	0.2	4.7	4.6	-
Total N	29.5	14.3	11.4	61
Total P	10.1	8.1	7.1	30
Turbidity, NTU	-	1.7	1.6	-
Color, Pt-Co units	-	17	18	-

TABLE 30. RESULTS OF RUN U7

	Influent					Effluent					
Parameter	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow, 1/sec	54	1.95	3.40	3.09	-	-	-	-	-	-	-
Turbidity,NTU	48	0.6	3.6	1.7	-	48	0.6	4.0	2.0	-	-
TSS, mg/1	53	<1	21	4	-	53	<1	72	5	-	-
Color, Pt-Co Units	54	5	50	19	-	54	5	50	20	-	-
TOC,mg/1	51	6	20	12	-	51	7	20	12	-	-
COD, mg/1	53	8	77	26	-	53	4	69	25	-	-
Percent Trans-mittance at 254 nm	53	38.8	79.0	64.1	-	-	-	-	-	-	-
Standard Plate Count per ml	22	$2.8x10^4$	$3.3x10^5$	$5.6x10^4$	4.75	26	$2.6x10^1$	$1.0x10^3$	$8.9x10^1$	1.95	2.80
Total Coliforms per 100 ml	54	$5.0x10^4$	$3.5x10^7$	$6.3x10^5$	5.80	54	$<2.0x10^0$	$3.5x10^4$	$<1.9x10^2$	<2.28	>3.52
Fecal Coliforms per 100 ml	54	$1.7x10^4$	$4.9x10^6$	$<3.7x10^5$	<5.57	54	$<2.0x10^0$	$2.4x10^4$	$<1.0x10^2$	<2.00	>3.57

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

The improved biological treatment and the resulting higher quality effluent had a pronounced effect on the UV disinfection process. The geometric mean fecal and total coliform densities were less than 100 per 100 ml and 190 per 100 ml, respectively, greater than one-log improvement over the results obtained during the previous run.

The coliform organisms were reduced slightly more than 3.5 logs. This is not as good as the greater than 4-log reductions observed during Runs U1, U2, and U3; however, the UV doses used during these runs were approximately double the dose used during this run.

Time-series plots of the microbiological data are shown in Figures 98, 99, and 100, while Figures 101, 102, and 103 present the extreme-value probability distributions.

The very significant improvement in disinfection that resulted from improved treatment is clear in the time-series plots. The effluent coliform densities decreased approximately two logs on August 9.

UV intensity, as measured by the IL 500 radiometer at the quartz window, was plotted versus observed log reductions in total and fecal coliforms. Poor correlations were obtained. For total coliforms the equation of the line obtained by linear regression analysis was $\log y = 0.064\ x - 4.14$. The correlation coefficient obtained was 0.39. For fecal coliforms, the equation obtained was $\log y = 0.057\ x - 4.11$. The correlation coefficient was 0.28.

RUN NO. U8

The last UV disinfection run was started on 7 October and terminated on 31 November 1975. As shown in Figure 104, activated sludge effluent was pumped directly to the UPS unit. Water quality data for the No. 1 activated sludge system are summarized in Table 31. Treatment was adequate, as indicated by the moderately low mean COD and TSS concentrations. Nitrification was incomplete, with an average of 5.4 mg/l of ammonia nitrogen being found in the effluent.

The objective of this run was to stress the disinfection capabilities of the UPS unit as much as possible. For this reason the unit was operated at the maximum obtainable flow of 3.2 liters/sec (51 gpm). The resulting theoretical and actual residence times were 16.8 and 15.0 seconds, respectively. An extinction coefficient, k, of 0.50 cm^{-1} resulted from the mean transmissability at 254 nm of 61.2 percent. The theoretical, calculated dose, D_T, was 11,500 μwatt-sec./cm^2. The average intensity measured with IL 500 radiometer was 100 μwatt-sec./cm^2 which resulted in an indicated dose, D_I, of 13,400 μwatt-sec/cm^2 after being corrected for geometry and multiplied by the actual residence time.

Data from the microbiological samples are presented in Table 32. During this run the mean coliform reductions were slightly less than three logs, which is not as good as had been observed in previous runs when the

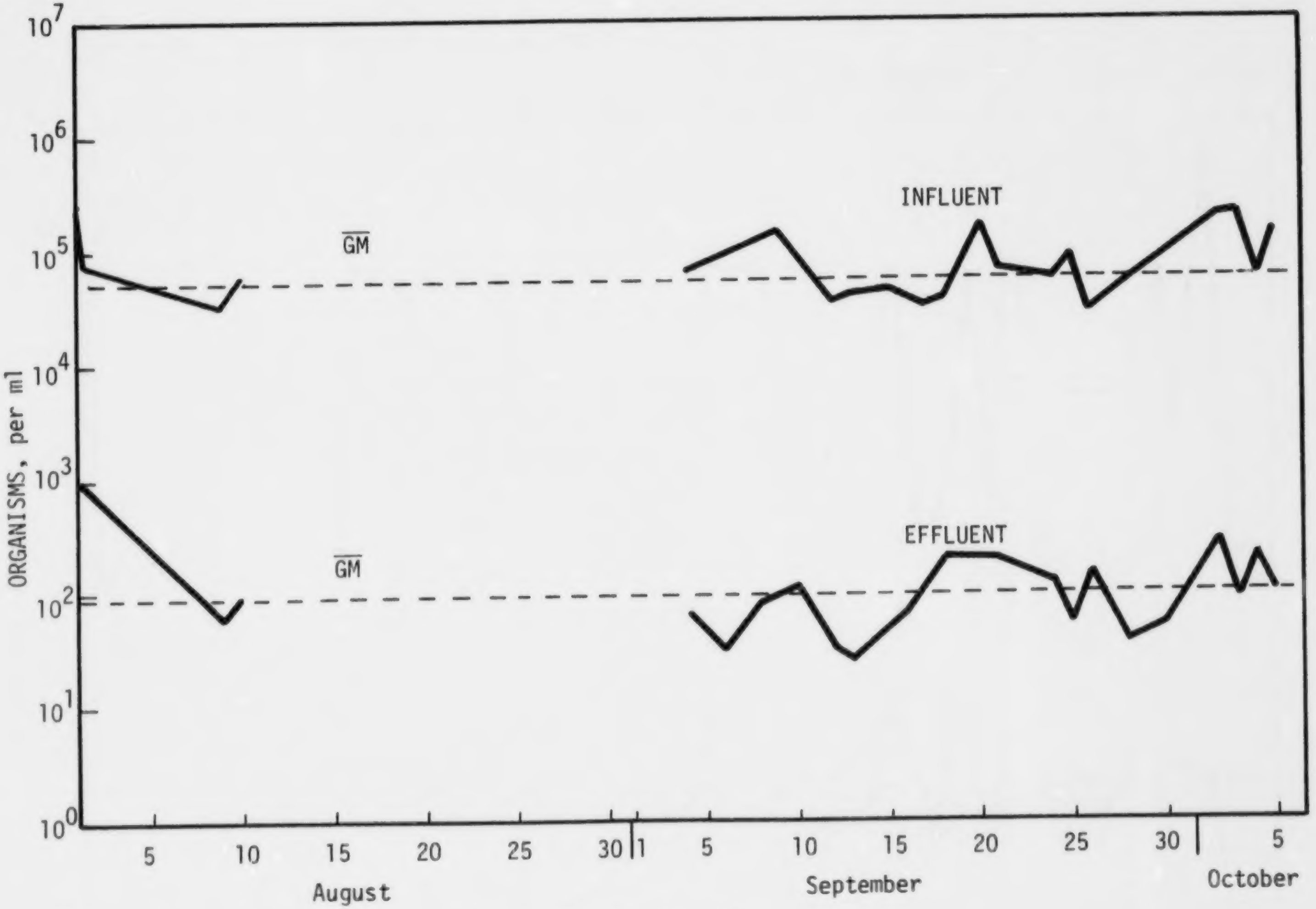


Figure 98. Standard plate count data for Run No. U7.

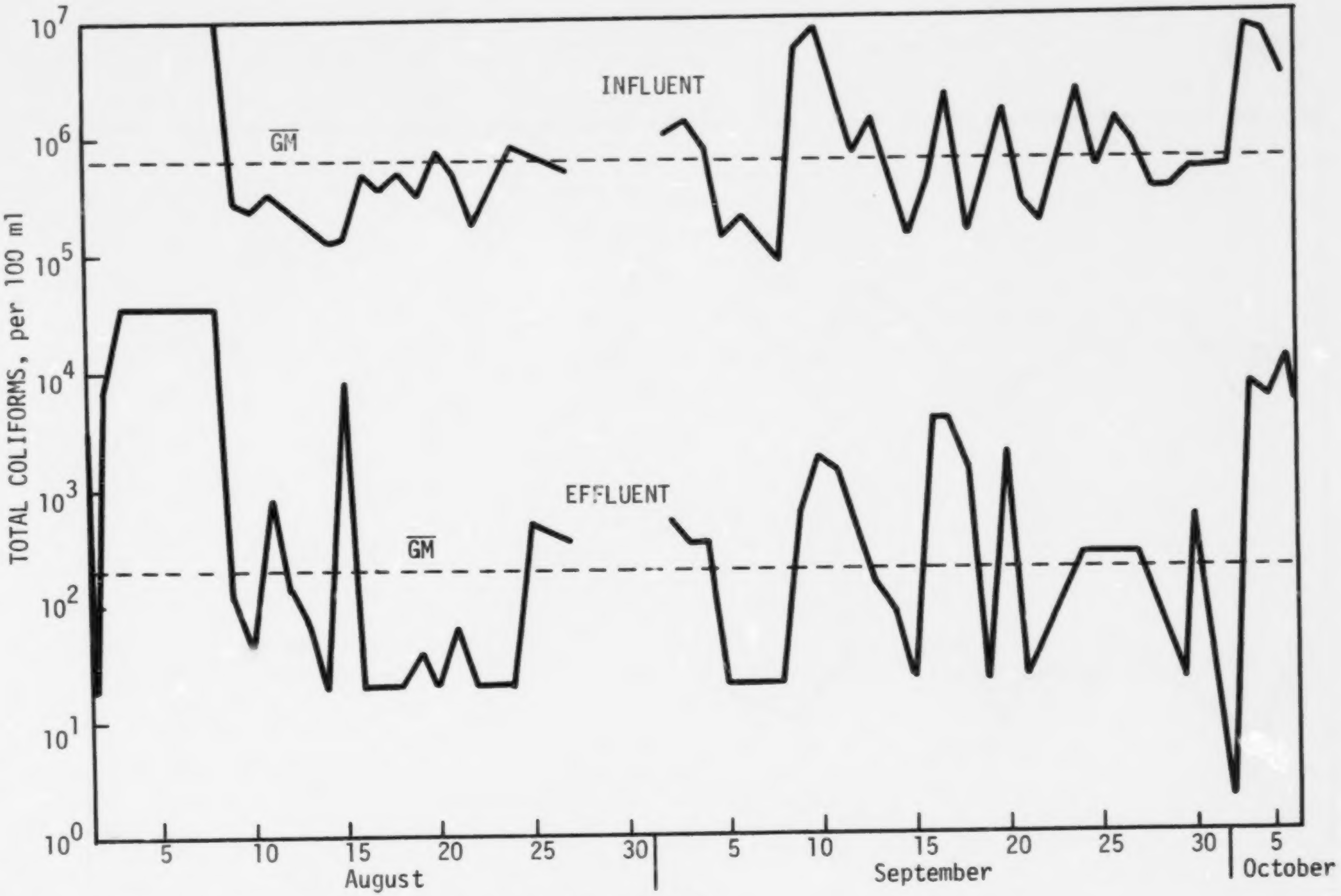


Figure 99. Total coliform data for Run No. U7.

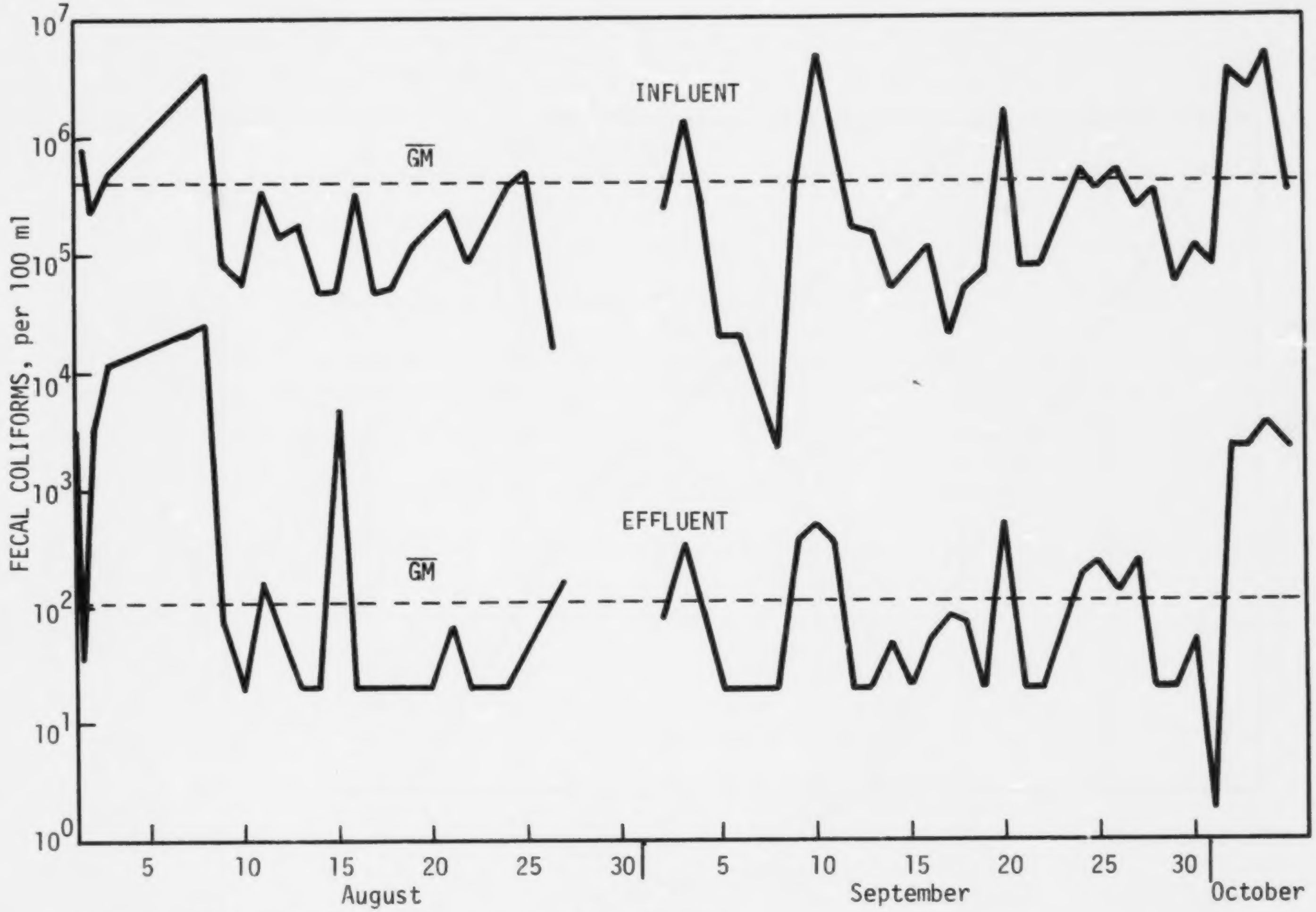


Figure 100. Fecal coliform data for Run No. U7.

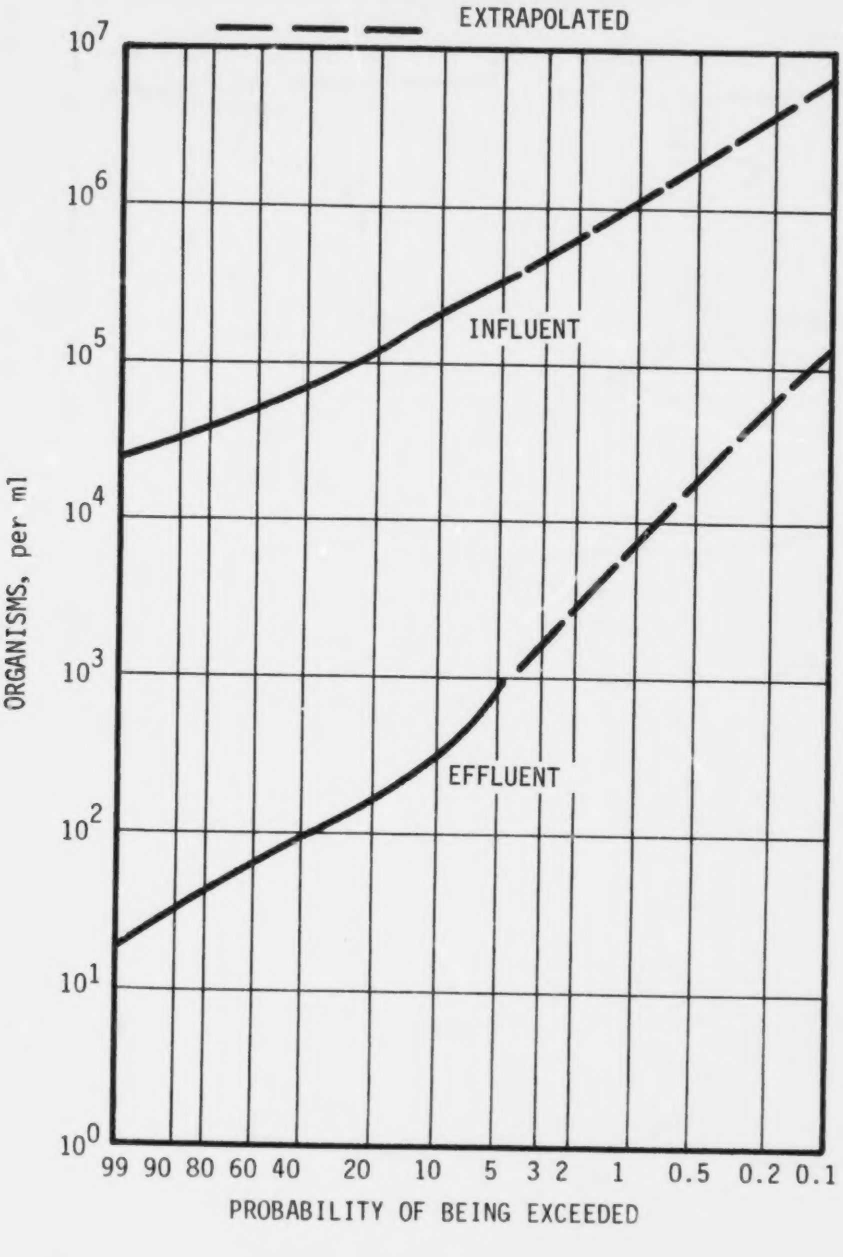


Figure 101. Extreme-value frequency distribution of standard plate count data for Run No. U7.

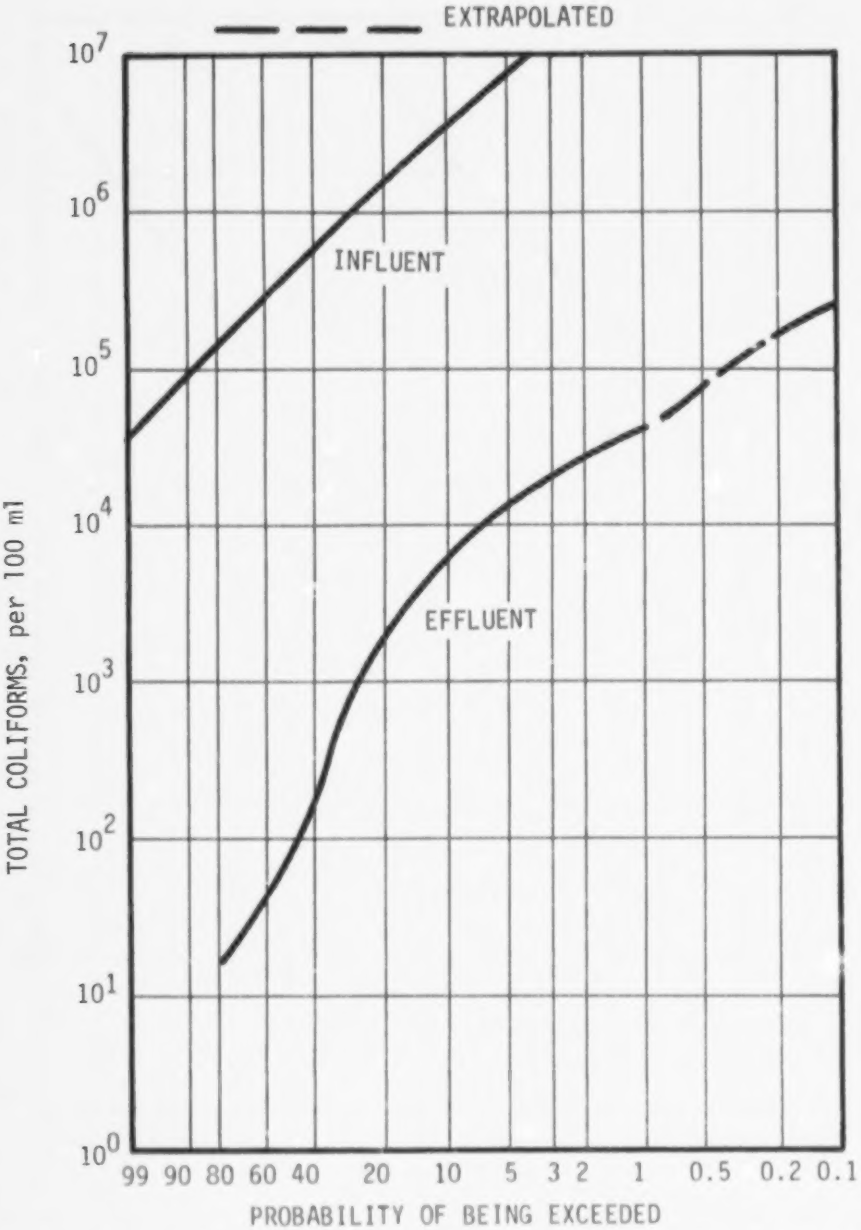


Figure 102. Extreme-value frequency distribution of total coliform data for Run No. U7.

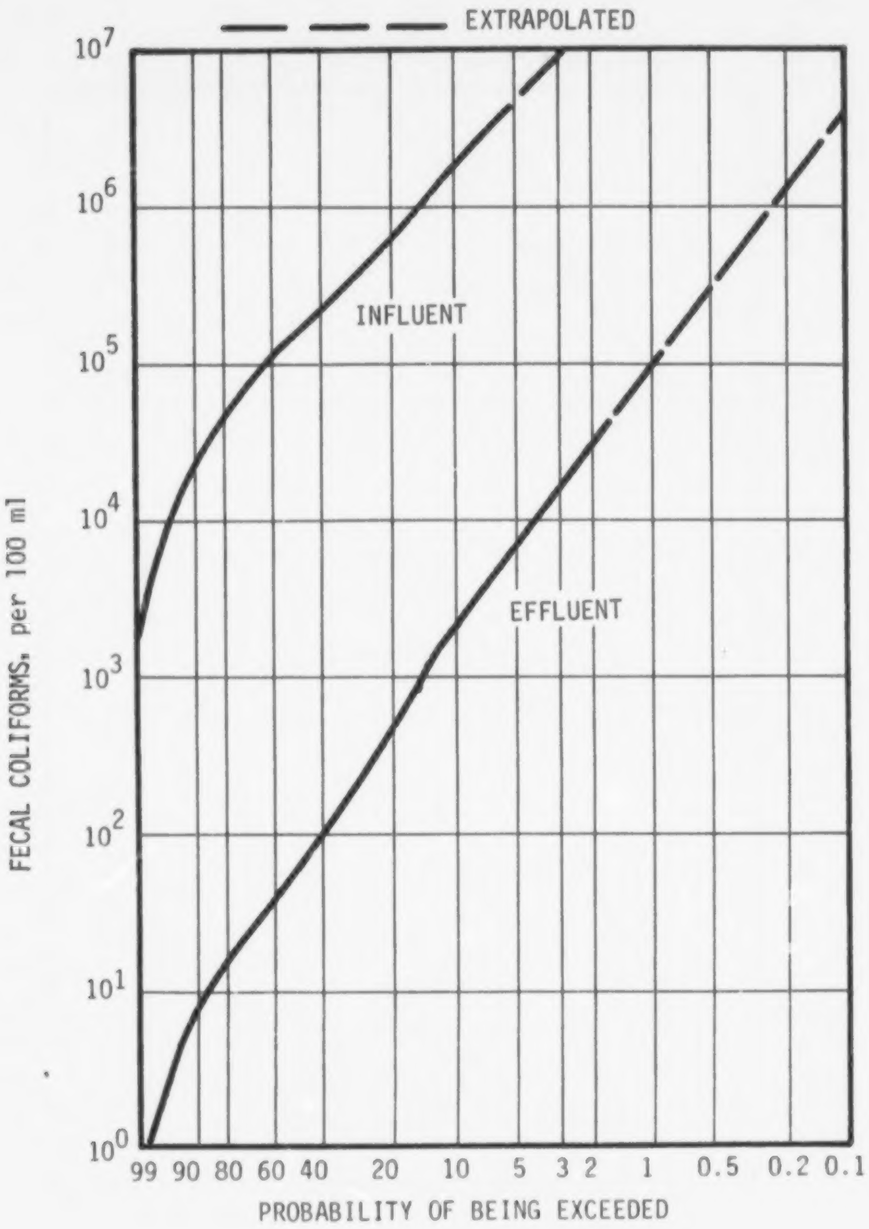


Figure 103. Extreme-value frequency distribution of fecal coliform data for Run No. U7.

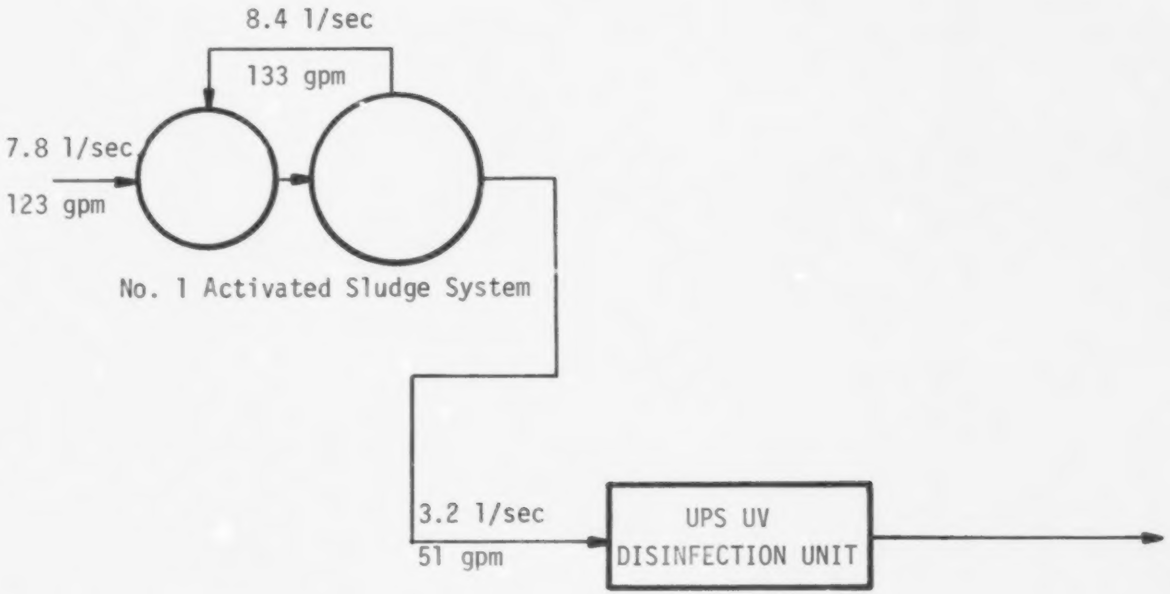

8.4 l/sec
133 gpm
7.8 l/sec
123 gpm
No. 1 Activated Sludge System
3.2 l/sec
51 gpm
UPS UV
DISINFECTION UNIT

Figure 104. Pilot Plant configuration for Run No. U8; October 7 to November 31, 1975.

TABLE 31. PERFORMANCE OF THE NO. 1 ACTIVATED SLUDGE SYSTEM DURING RUN NO. U8

Parameter	Influent mg/l	Effluent mg/l	Removal percent
TSS	91	17	81
COD/COD sol	310	63.4/33.9	80
TOC, soluble	61.2	13.9	77
NH_3-N	22.7	5.4	76
Org.-N	11.8	3.7	69
NO_2 & NO_3-N	0.4	6.7	-
Total N	34.9	15.8	55
Total P	10.0	8.0	20
Turbidity, NTU	7.4	7.7	-

TABLE 32. RESULTS OF RUN U8

	Influent					Effluent					
Parameter	N	Min	Max	Mean[1]	Log of Mean[2]	N	Min	Max	Mean[1]	Log of Mean[2]	Mean Log Reduction[2]
Flow, l/sec	45	2.39	3.65	3.21	-	-	-	-	-	-	-
Turbidity,NTU	42	1.3	18	7.4	-	42	1.3	18	7.4	-	-
TSS, mg/l	38	2	62	13	-	39	2	62	14	-	-
Color, Pt-Co Units	-	-	-	-	-	-	-	-	-	-	-
TOC, mg/l	44	6	15	12	-	44	6	15	11	-	-
COD, mg/l	44	23	57	37	-	44	24	89	38	-	-
Percent Transmittance at 254 nm	38	53.5	68.0	61.2	-	-	-	-	-	-	-
Standard Plate Count per ml	33	2.0×10^4	3.4×10^5	1.1×10^5	5.04	31	2.9×10^2	2.5×10^3	7.9×10^2	2.90	2.14
Total Coliform per 100 ml	44	1.1×10^5	1.1×10^7	9.0×10^5	5.95	45	8.0×10^1	5.4×10^4	$<9.8\times10^2$	<2.99	>2.96
Fecal Coliform per 100 ml	44	$<2.0\times10^4$	1.7×10^6	$<2.9\times10^5$	<5.46	45	$<2.0\times10^1$	3.3×10^3	$<4.2\times10^2$	<2.62	2.84

1. Geometric means are reported for all microbiological data.

2. Reported for microbiological data only.

quality of the activated sludge effluent was good. Additionally, the effluent total and fecal coliform densities were somewhat higher than in previous runs with effluent of similar quality.

The combination of decreased residence time and the relatively low percent transmittance resulted in one of the lowest UV doses used during the project. The calculated dose, D_T, during Run U8 was only about one-third of the dose used during Run U1 through U3, and was about one-half of the dose used during Runs U4 and U5. The dose used during Run U7 was approximately 30 percent higher than the 11,500 μwatt-sec./cm^2 used during this run. The low dose used was the reason for the decrease in disinfection efficiency.

Figures 105, 106, and 107 are time-series plots of the microbiological data. The apparent variation in bacterial densities in the UV disinfected effluent is approximately one log either side of the geometric mean. The effect of the variability can be seen in the extreme-value frequency distributions in Figures 108, 109, and 110. The indication is that 50 percent of the time a fecal coliform density of about 320 per 100 ml will be exceeded, and that a density of 400 fecal coliforms per 100 ml will be exceeded approximately 45 percent of the time.

As in Run U7 poor correlations were observed when UV intensity was plotted versus observed log reductions in total and fecal coliforms. When plotted versus log reduction of total coliforms the equation of the line obtained by linear regression analysis was $\log y = 0.048\, x - 3.79$. The correlation coefficient for this line was - 0.15. When plotted versus log reduction of fecal coliforms the equation obtained was $\log y = 0.035\, x - 3.83$. The correlation coefficient for the line was - 0.09.

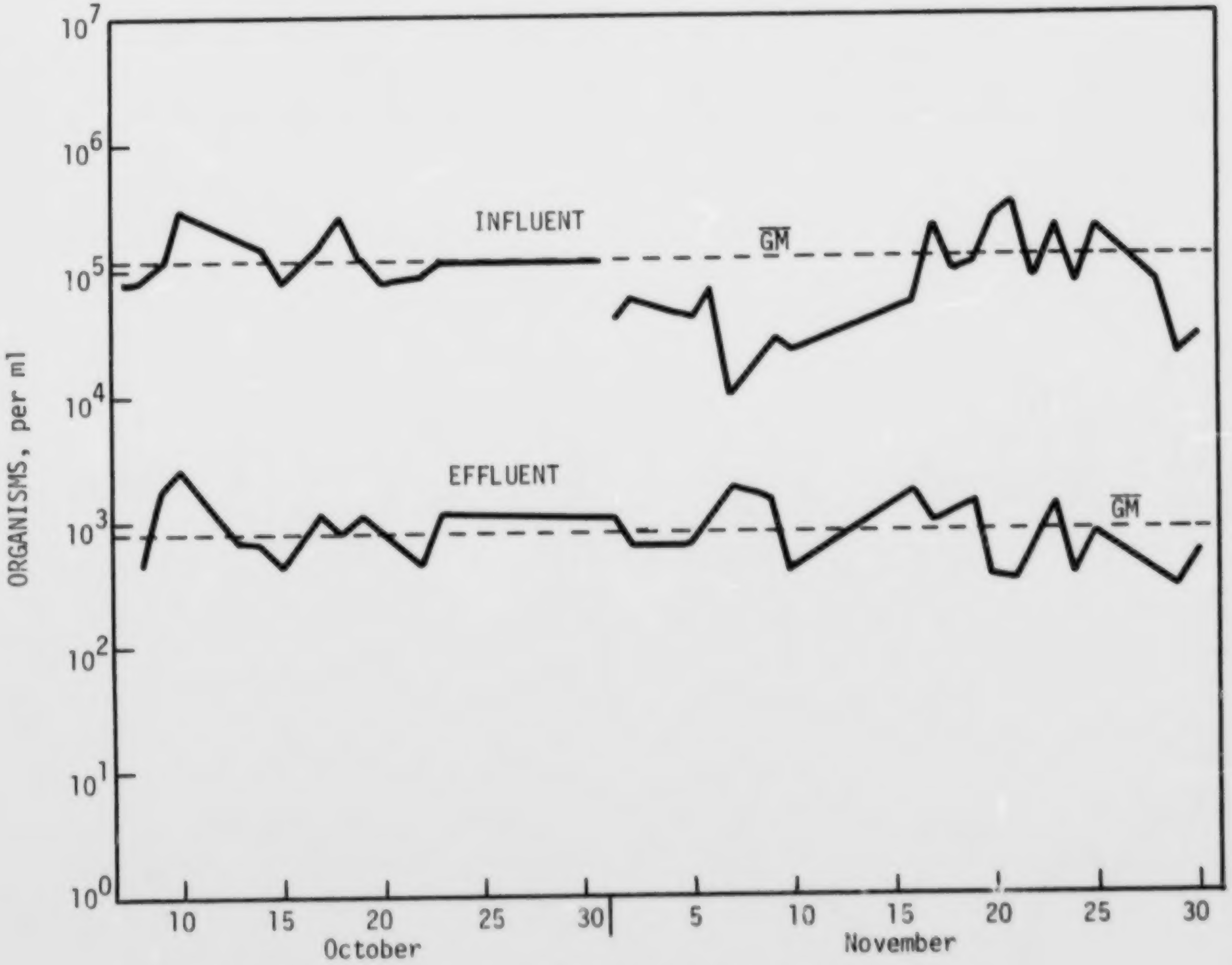


Figure 105. Standard plate count data for Run No. U8.

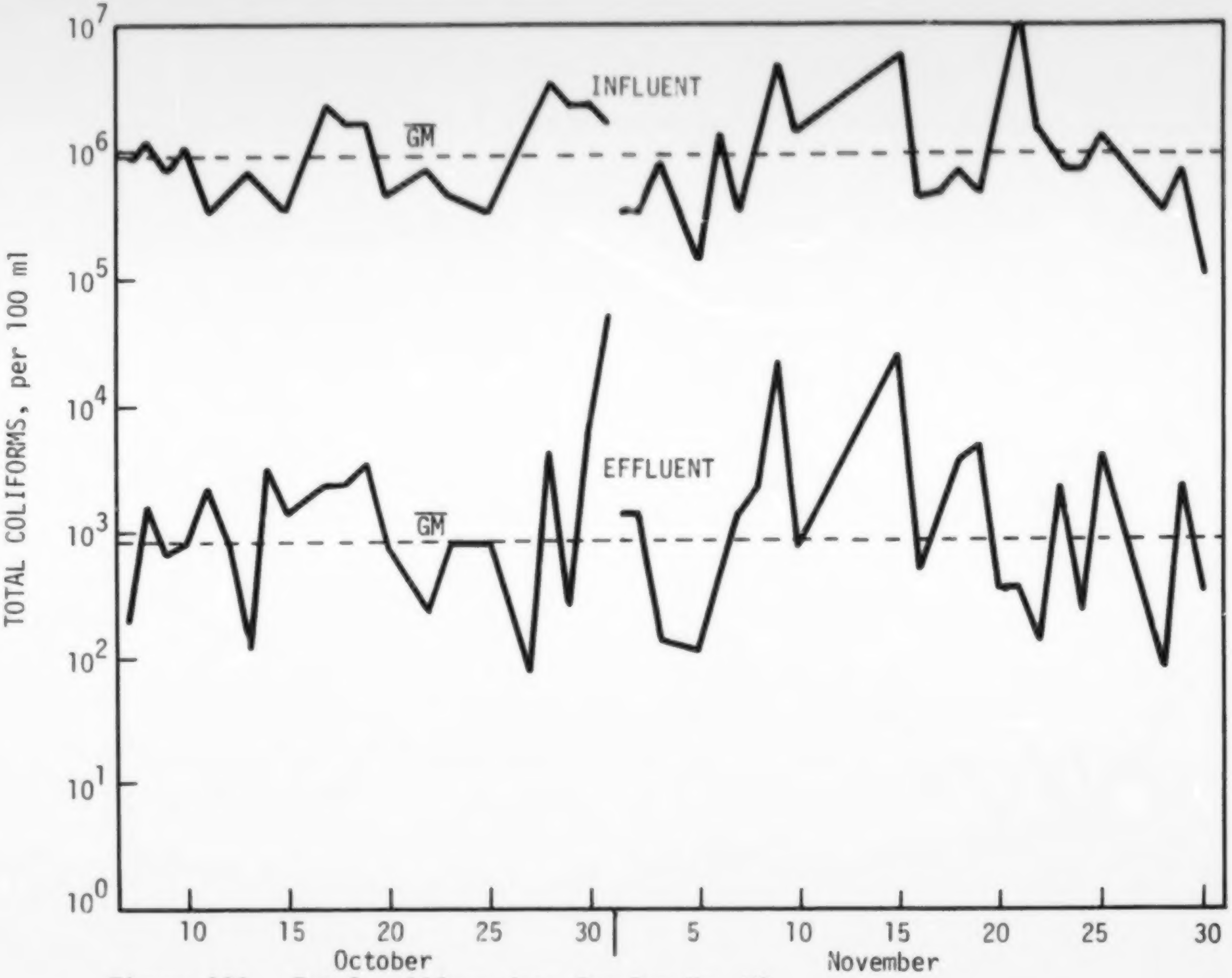


Figure 106. Total coliform data for Run No. U8.

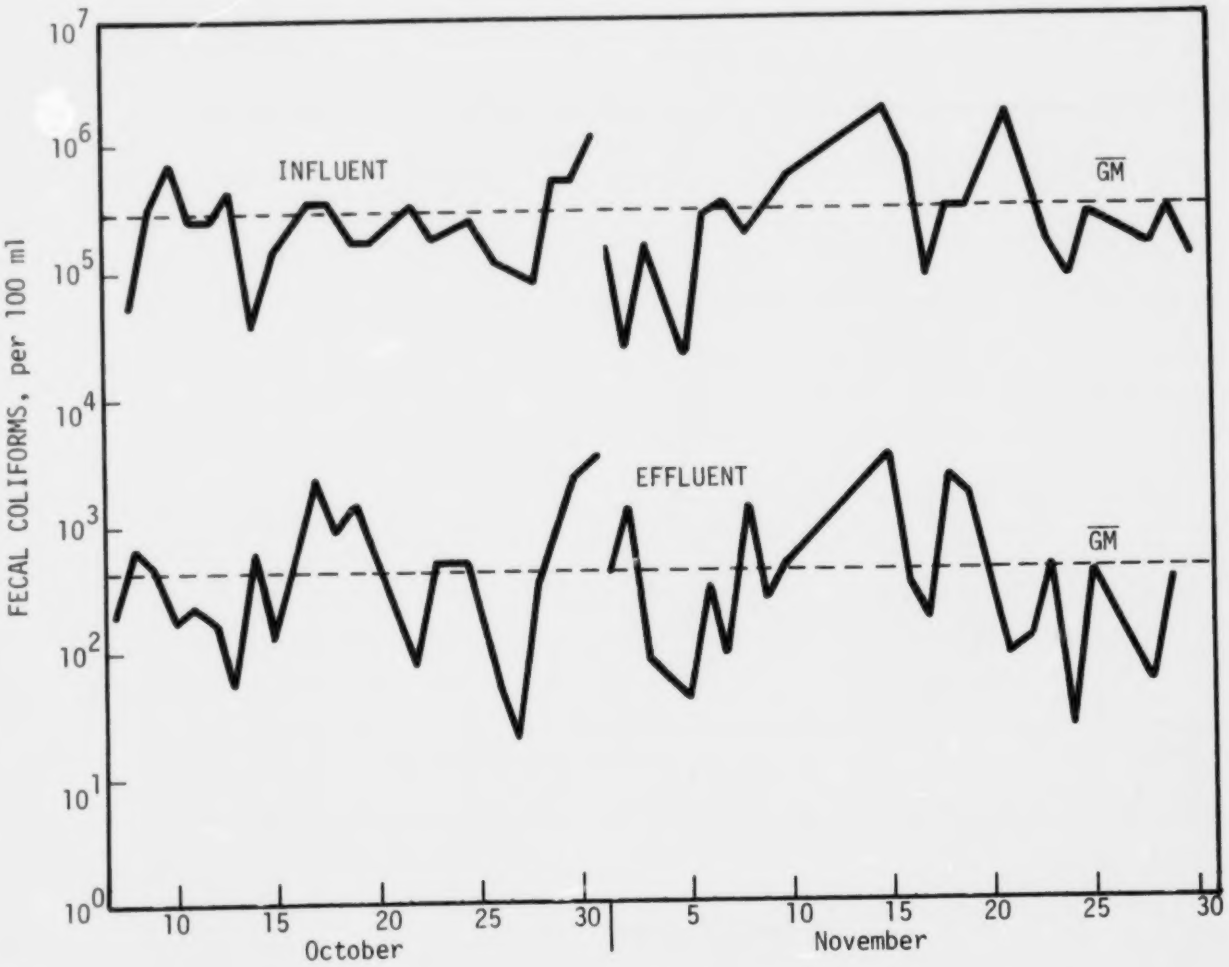


Figure 107. Fecal coliform data for Run No. U8.

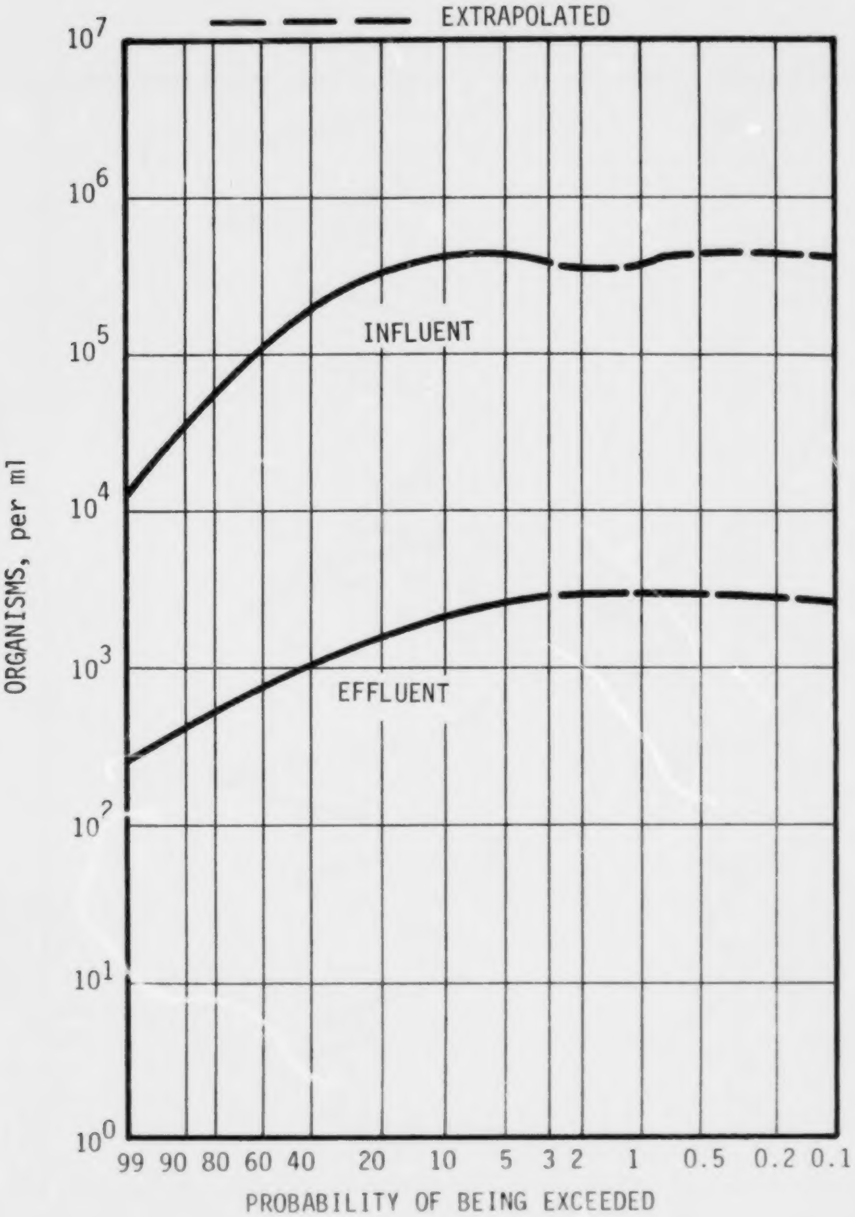


Figure 108. Extreme-value frequency distribution of standard plate count data for Run No. U8.

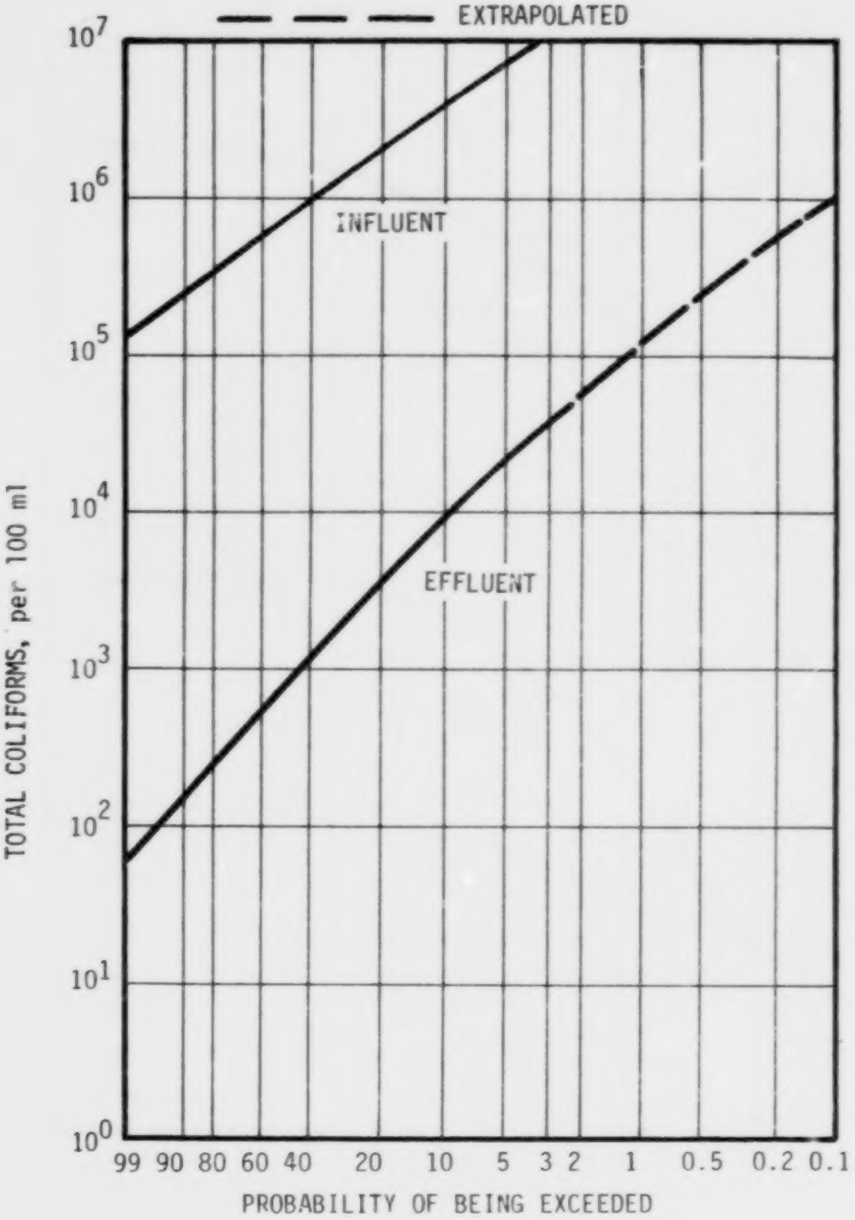


Figure 109. Extreme-value frequency distribution of total coliform data for Run No. U8.

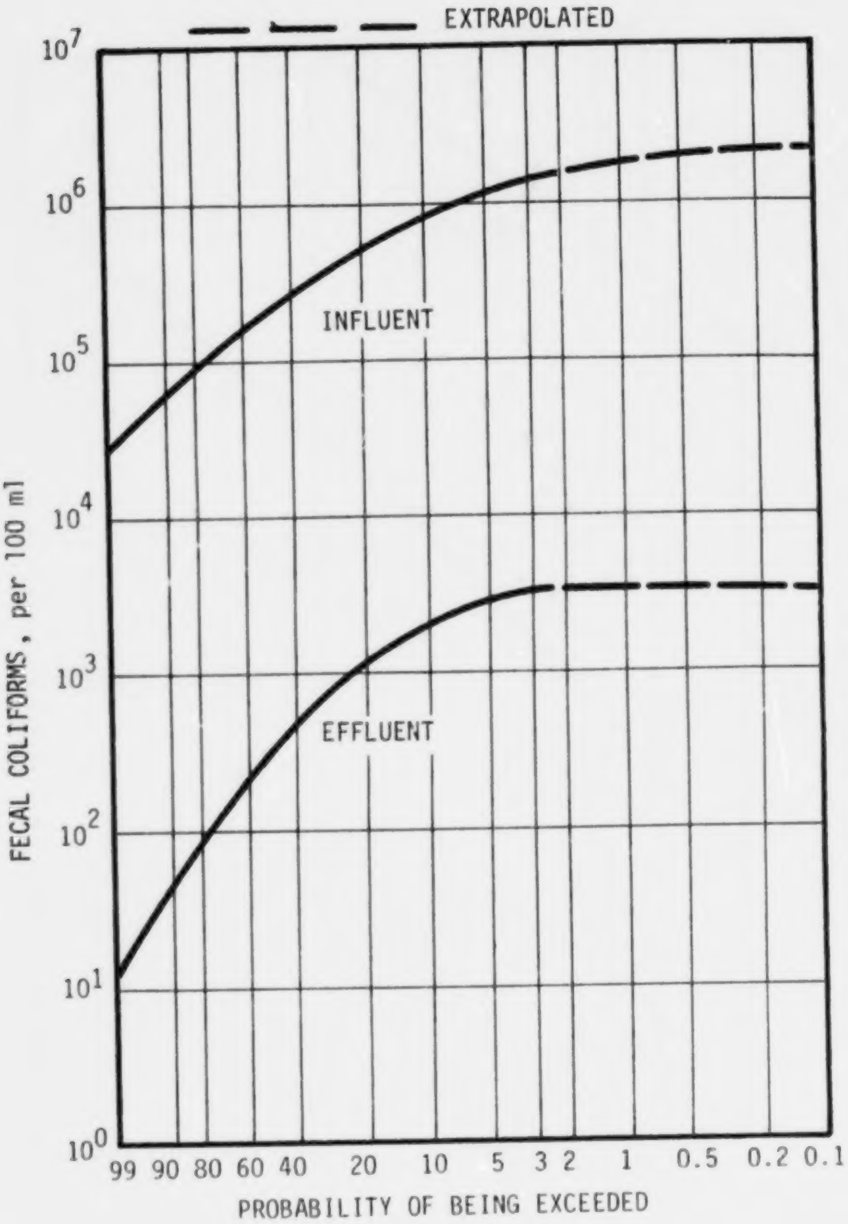


Figure 110. Extreme-value frequency distribution of fecal coliform data for Run No. U8.

SECTION 8

VIRUS STUDIES

One of the objectives of the project was to evaluate the comparative resistance of poliovirus, F2 bacteriophage, and total and fecal coliform bacteria to ultraviolet radiation. The poliovirus strain used was an attenuated Type I culture obtained from Dr. G. Berg, U.S. E.P.A., Cincinnati, Ohio.

A total of three replicate experiments were conducted on the following dates: (1) 22 April 1975, (2) 13 May 1975, and (3) 26 June 1975. Initial volume of poliovirus seed was approximately 3.2 liters, containing approximately $8x10^7$ plaque forming units (pfu) per ml. Bacterial virus F2 was added to the poliovirus culture at a titer of $3x10^8$ pfu per ml.

Figure 111 illustrates schematically the flow diagram of a typical run. Activated sludge effluent was used as a wastewater source. The virus/phage seed was pumped into the effluent stream at a rate of 100 ml/minute on the suction side of a centrifugal pump, where the seed became well mixed with the effluent prior to entering the UPS UV unit. After emerging from the UV unit the effluent flowed into chlorine contact basins, where a very high chlorine residual was maintained to destroy any poliovirus which might have survived the UV irradiation. Three sample taps were located as shown in the diagram.

After collecting the control samples the UV lamps were energized and allowed to reach their peak output. Ultraviolet intensity readings were made with the IL 500 radiometer, and the water quality meter provided with the UPS unit. After the warm-up time, three separate test samples were collected for virus enumeration (1) prior to virus/phage addition (for indigenous virus), (2) after the pump, but before the UV unit, and (3) after the UV unit. Three duplicate samples were collected one minute later, and another duplicate set, one minute after that. This entire protocol was repeated at all four wastewater flow rates.

In order to protect the chemists and biologists from poliovirus exposure, the bacteriology and chemistry samples were collected prior to addition of the virus/phage inoculum to the wastewater, but with the UV unit at steady state and the lamps on. No chemical analyses were performed on the seeded samples.

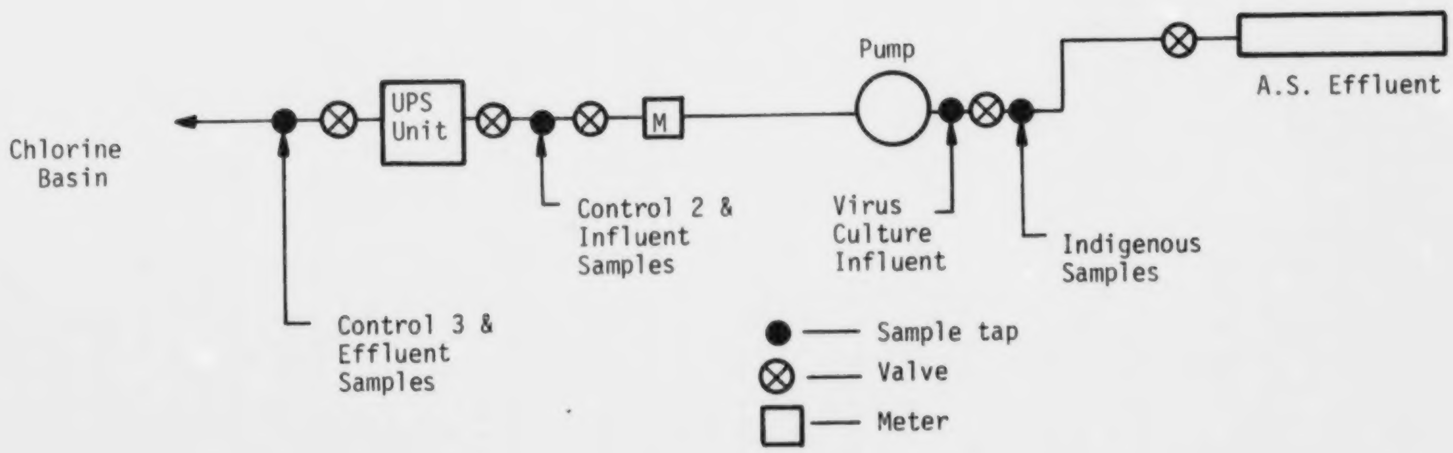

Chlorine
Basin
UPS
Unit
M
Pump
A.S. Effluent
Control 3 &
Effluent
Samples
Control 2 &
Influent
Samples
Virus
Culture
Influent
Indigenous
Samples
Sample tap
Valve
Meter

Figure 111. Location of sampling stations, UV Virus Runs.

FIRST UV VIRUS RUN

An operating summary of the UV unit for the first virus run appears on Table 33. The hydraulic characteristics and start-finish meter readings are presented for each of the flow conditions investigated.

A summary of the chemical characteristics of the wastewater before and after exposure to UV radiation averaged over all four flow rates is given in Table 34. No significant change in any wastewater quality variable, except possibly BOD, was observed. A summary of the bacteriological data is given in Table 35. It is clear that, as wastewater flow rate decreased, total and fecal coliform reduction increased. This was expected, since a decrease in flow rate corresponds to an increase in residence time, and thus, an increase in exposure time to UV irradiation. It also appears that total and fecal coliforms displayed approximately the same relative resistance to UV irradiation.

Results from the phage seeding experiments are given in Table 36 (control sampling) and 37 (test sampling). The purpose of the control sampling was to establish the attainment of steady-state conditions at each flow rate prior to the test sampling. The UV lamps were turned off during control sampling. Steady-state conditions were established when influent and effluent titers were the same.

No F2 phages were detected in either the Control 2 samples (before UV) or the Control 3 samples (after UV). The phage/poliovirus seed suspension was conveyed from a cubitainer 3 meters above the floor of the filter gallery through a metering pump and tygon tube. The 3-meter length of tygon tubing had been flushed with sterile distilled water prior to the run, and was still full of the water when the virus feed pump was activated. The virus/phage suspension had not completely displaced this water at the commencement of the first run (4.7 l/sec.), and as a result the influent titers were negative. This effect was not repeated in the three successive runs, because the line was not flushed between runs.

Steady state conditions were established at 3.2 and 1.9 l/sec (Table 36). At 0.6 l/sec, two of the Control 3 samples were negative for phage. This was presumably because the UPS UV unit had not been completely flushed following the last test run when the phage titer had been reduced by several logs. As a result the phage titer at the beginning of the control run was lower than expected, and thus the phage numbers were undetected because the dilutions were carried out too far.

Examination of Table 37 reveals that the number of indigenous phage present in the wastewater was insignificant relative to the F2 titer after seeding. It is also evident that F2 phage were undetected in the samples before and after the UV unit during the 4.7 l/sec run probably for the same reasons mentioned for the control samples. In general, it appears that F2 bacteriophage may be slightly more resistant to UV than total or fecal coliforms, as indicated by the mean log reduction values (Table 37).

TABLE 33. OPERATING SUMMARY OF THE FIRST UV VIRUS RUN

Flow Rates, l/sec	4.7	3.2	1.9	0.6
Theoretical t, sec.	11.4	16.8	28.2	85.1
100 percent flushing time, sec.	28	42	70	210
WQ Meter (Start), Dimensionless units - scale (0-40)	32	29	<20	30
WQ Meter (Finish), Dimensionless units (scale 0-40)	27	24	20	25
Radiometer (Start) $\mu w/cm^2$	550	550	550	550
Radiometer (Finish), $\mu w/cm^2$	530	540	540	540

TABLE 34. RESULTS OF CHEMICAL ANALYSES OF GRAB SAMPLES AVERAGED OVER ALL FOUR FLOW RATES IN THE FIRST VIRUS RUN.

Parameter	Influent to UV	Effluent from UV
COD, mg/l	46.2	47.9
TOC, mg/l	15.5	15.2
SOC, mg/l	10.0	10.8
BOD, mg/l	10	4.5
TSS, mg/l	20	22
Turbidity, NTU	2.8	2.8
Color, Pt-Co units	30	30
NH_3-N, mg/l	1.8	-
Org-N, mg/l	4.4	-
NO_2-N + NO_3-N	6.0	-
NO_2-N	0.3	-
D.O., mg/l	3.4	3.3
pH	7.4	7.3
Sp. Cond.	727	750
Total Alk., mg/l	131	-
p Alk., mg/l	0	-
TDS, mg/l	522	-
Cl^-, mg/l	58	-
%Transmittance at 254 nm	67.2	66.6

TABLE 35. SUMMARY OF THE BACTERIOLOGICAL DATA FROM THE FIRST VIRUS RUN.

Parameter	Flow Rate, 1/sec.							
	4.7		3.2		1.9		0.6	
	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
Total Coliforms 100 ml	1.3×10^{6}	2.6×10^{3}	1.7×10^{6}	5.0×10^{2}	7.9×10^{5}	8.0×10^{0}	7.9×10^{5}	$<2.0 \times 10^{0}$
Log Reduction	2.70		3.53		5.00		>5.60	
Fecal Coliforms per 100 ml	2.2×10^{5}	4.0×10^{2}	1.1×10^{5}	2.0×10^{2}	7.9×10^{4}	2.0×10^{0}	1.3×10^{5}	$<2.0 \times 10^{0}$
Log Reduction	2.74		2.74		4.60		>4.81	

TABLE 36. STEADY-STATE TITERS OF F2 BACTERIOPHAGE CONTROLS IN FIRST VIRUS RUN.

Sample	Phage titers, pfu/ml Detention time, sec (Flow Rate, l/sec) 11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6)
Control 2 Before UV				
30 sec	$< 2.0\times10^{0}$	4.3×10^{4}	1.4×10^{5}	5.0×10^{4}
60 sec	$< 2.0\times10^{0}$	3.6×10^{4}	7.6×10^{4}	1.0×10^{4}
90 sec	$< 2.0\times10^{0}$	8.3×10^{4}	1.2×10^{5}	4.2×10^{5}
Geometric Mean	2.0×10^{0}	5.0×10^{4}	1.1×10^{5}	5.9×10^{4}
Control 3 After UV				
30 sec	$< 2.0\times10^{0}$	5.3×10^{4}	7.8×10^{4}	$<2.0\times10^{0}$
60 sec	$< 2.0\times10^{0}$	7.1×10^{4}	7.1×10^{4}	$<2.0\times10^{0}$
90 sec	$< 2.0\times10^{0}$	1.2×10^{5}	3.9×10^{4}	1.2×10^{6}
Geometric Mean	$< 2.0\times10^{0}$	7.7×10^{4}	6.0×10^{4}	$<1.7\times10^{2}$
Control 1 SEED CULTURE				
	3.2×10^{8}			
	2.8×10^{8}			

TABLE 37. TITERS OF F2 BACTERIOPHAGE EXPOSED TO ULTRAVIOLET RADIATION AT DIFFERENT FLOW RATES IN FIRST VIRUS RUN.

	Phage Titers, pfu/ml			
	Detention Time, sec (Flow Rate, l/sec)			
Sample	11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6)
INDIGENOUS PHAGE				
0 sec	$1.7x10^{2}$	$9.5x10^{1}$	$4.9x10^{1}$	$1.1x10^{2}$
60 sec	$2.7x10^{2}$	$9.8x10^{1}$	$6.3x10^{1}$	$6.5x10^{1}$
120 sec	$1.2x10^{2}$	$1.1x10^{2}$	$6.2x10^{1}$	$1.1x10^{2}$
Geometric Mean	$1.8x10^{2}$	$1.0x10^{2}$	$5.8x10^{1}$	$9.2x10^{1}$
F2 Phage Before UV Unit*				
0 sec	$<1x10^{3}$	$2.8x10^{4}$	--	$7.7x10^{5}$
60 sec	$<1x10^{3}$	$5.9x10^{4}$	$4.4x10^{4}$	$6.0x10^{4}$
120 sec	$<1x10^{3}$	$2.8x10^{4}$	$9.6x10^{4}$	$2.9x10^{5}$
Geometric Mean	$<1x10^{3}$	$3.6x10^{4}$	$6.5x10^{4}$	$2.4x10^{5}$
F2 Phage After UV Unit*				
0 sec	$>1x10^{3}$	$3.9x10^{2}$	$1.1x10^{2}$	$5.4x10^{1}$
60 sec	$>1x10^{3}$	$3.6x10^{2}$	$1.6x10^{2}$	$8.0x10^{0}$
120 sec	$>1x10^{3}$	$6.8x10^{2}$	$1.8x10^{2}$	$1.1x10^{1}$
Geometric Mean	-	$4.6x10^{2}$	$1.5x10^{2}$	$1.7x10^{1}$
Log Reduction	-	1.90	2.63	4.15

*UV light had been on for two minutes.

Results from the poliovirus seeding experiments are summarized in Table 38. Poliovirus was undetectable in the control samples during the 4.7 l/sec run due to the incomplete flushing of sterile distilled water from the feed line. It is clear that steady-state flow conditions were established at the other three flow rates, as indicated by the comparable virus titers between the Control 2 and Control 3 samples at each flow condition. Mean log reduction of poliovirus increased with decreasing flow rate (or increasing detention time). Also, poliovirus appears to have elicited a similar response to UV inactivation as coliform bacteria. A complete summary of the first virus run is given in Table 39.

A summary of the dose-related data for the first UV run appears in Table 40. Dosages were calculated as enumerated in Section 7. The very high indicated doses, D_I, were a direct result of the high intensity readings. The highest doses, D_I, were obtained during this run, as well as the best disinfection, for both viruses and coliforms.

SECOND UV VIRUS RUN

The second poliovirus run with the UPS unit was conducted on 13 May 1975. On the afternoon of 12 May, the UV unit was turned off, taken out of service, cleaned with a proprietary cleaning solution provided by UPS, Inc., rinsed with tap water, and drained. Early the following morning it was refilled and flushed again with tap water. The lamps were then turned on, and intensity readings with the UPS water quality meter and IL 500 radiometer were recorded every 30 seconds for a period of 5 minutes. Figure 112 shows the responses. Maximum output was attained approximately 1.5 minutes after startup. The lamps were then turned off for a period of 5 minutes, but tap water flushing continued. Then the lamps were turned on, and again the readings were recorded, as shown in Figure 113. This time, the response was much quicker, as the maximum output was attained after only 1 minute. Following this, the lamps were turned off, and activated sludge effluent was valved into the unit for the first time since the cleaning. About 15 minutes later the lamps were turned on, and meter readings were recorded, as shown on Figure 114. The response was significantly different from the tap water readings. First, the UV output reached a maximum level after only 20 seconds, and the maximum output was higher than that recorded on tap water. Then, between 2 minutes and 4 minutes the intensity declined from 110 to 100 μwatts/cm^2. At the same time, the water quality meter responded much differently, reaching a maximum value of only 10 after 30 seconds, but remaining unchanged thereafter.

The ultraviolet intensity readings of 100 to 110 μwatt/cm^2 on tap water were unusual in that in previous disinfection runs intensity readings of approximately 550 μwatts/cm^2 on wastewater effluent had been obtained. There are several possible reasons for the low intensity readings. First, film build-up on the quartz sleeves might have been inadequately removed. Second, the proprietary cleaning compound used may absorb UV light. If the

TABLE 38. TITERS OF POLIOVIRUS TYPE I EXPOSED TO UV RADIATION AT DIFFERENT FLOW RATES IN FIRST VIRUS RUN.

	Virus Titers, pfu/ml			
	Detention Time, sec (Flow Rate, 1/sec)			
Sample	11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6)
Control 2-before UV				
30 sec	0	9.2×10^3	1.2×10^4	3.9×10^4
60 sec	0	8.2×10^3	1.5×10^4	5.0×10^4
90 sec	0	7.9×10^3	1.1×10^4	5.1×10^4
Geometric Mean	0	8.4×10^3	1.3×10^4	4.6×10^4
Control 3-after UV				
30 sec	0	6.0×10^3	1.2×10^4	2.6×10^3
60 sec	0	8.0×10^3	1.3×10^4	1.4×10^4
90 sec	0	1.1×10^4	1.3×10^4	2.2×10^4
Geometric Mean	0	8.0×10^3	1.3×10^4	9.3×10^3
Before UV Unit*				
0 sec	5.8×10^3	1.2×10^4	9.7×10^3	3.7×10^4
60 sec	6.8×10^3	1.0×10^4	1.1×10^4	5.4×10^4
120 sec	8.6×10^3	1.0×10^4	1.3×10^4	4.5×10^4
Geometric Mean	7.0×10^3	1.1×10^4	1.1×10^4	4.5×10^4
After UV Unit*				
0 sec	2.8×10^1	9.0×10^0	1	0
60 sec	7.2×10^1	1.0×10^1	0	3
120 sec	5.9×10^1	4.0×10^0	1	0
Geometric Mean	4.9×10^1	7×10^0	<1	$<1.4 \times 10^0$
Log Reduction	2.15	3.23	>4.04	>4.49

*UV lights had been on for 2 minutes.

Other Results:

All samples from the Cl_2 contact basin were 0 .

All samples of indigenous virus were 0.

Control 1 (virus feed): start = 3.8×10^7 PFU/ml
end = 2.9×10^7 PFU/ml

TABLE 39. SUMMARY OF RESULTS FROM FIRST VIRUS RUN.

Organism	MEAN LOG REDUCTIONS Detention Time, sec (Flow Rate, l/sec) 11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6)
Total Coliforms	2.70	3.53	5.00	>5.60
Fecal Coliforms	2.74	2.74	4.60	>4.81
F_2 Bacteriophage	-	1.90	2.63	4.15
Poliovirus Type 2	2.15	3.23	4.04	>4.49

TABLE 40. SUMMARY OF DOSE-RELATED DATA FOR THE FIRST VIRUS RUN

Flow Rate, l/sec	4.7	3.2	1.9	0.6
Theoretical Detention Time, sec	11.4	16.8	28	85
Actual Detention Time, sec	10	15.5	25	75
Transmittance @ 254 nm, percent	66.9	66.9	66.9	66.9
Extinction Coefficient cm^{-1}	0.41	0.41	0.41	0.41
UV Intensity, $\mu watt/cm^2$	540	545	545	545
Calculated Dose, D_T, $\mu watt\text{-}sec/cm^2$	11,200	16,500	27,500	83,400
Indicated Dose, D_I, $\mu watt\text{-}sec/cm^2$	48,100	75,200	121,300	363,800

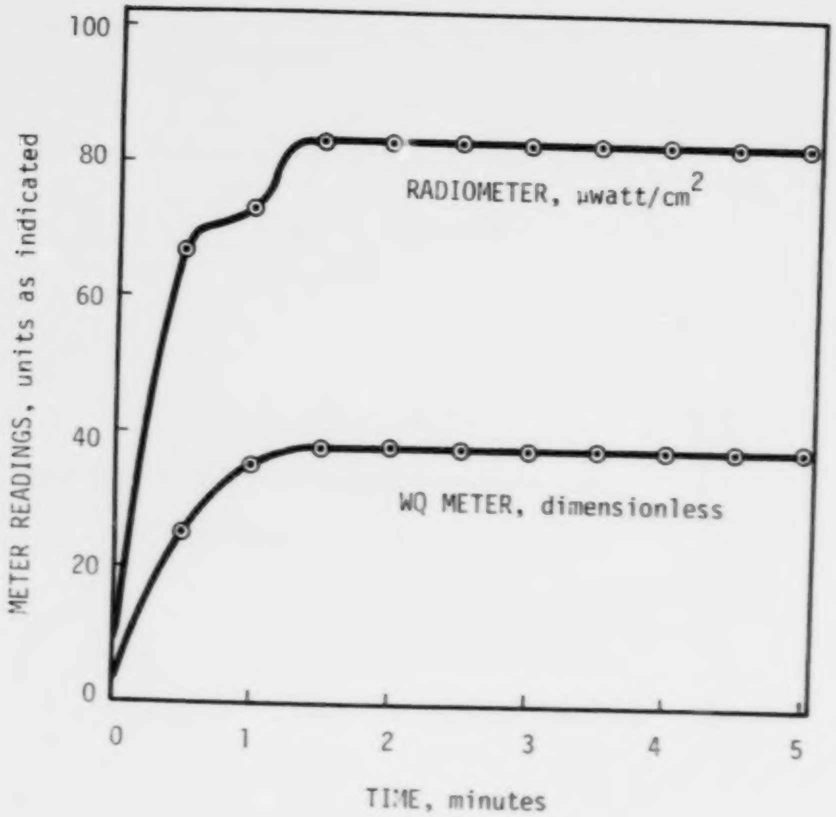


Figure 112. Meter readings with tap water from cold start.

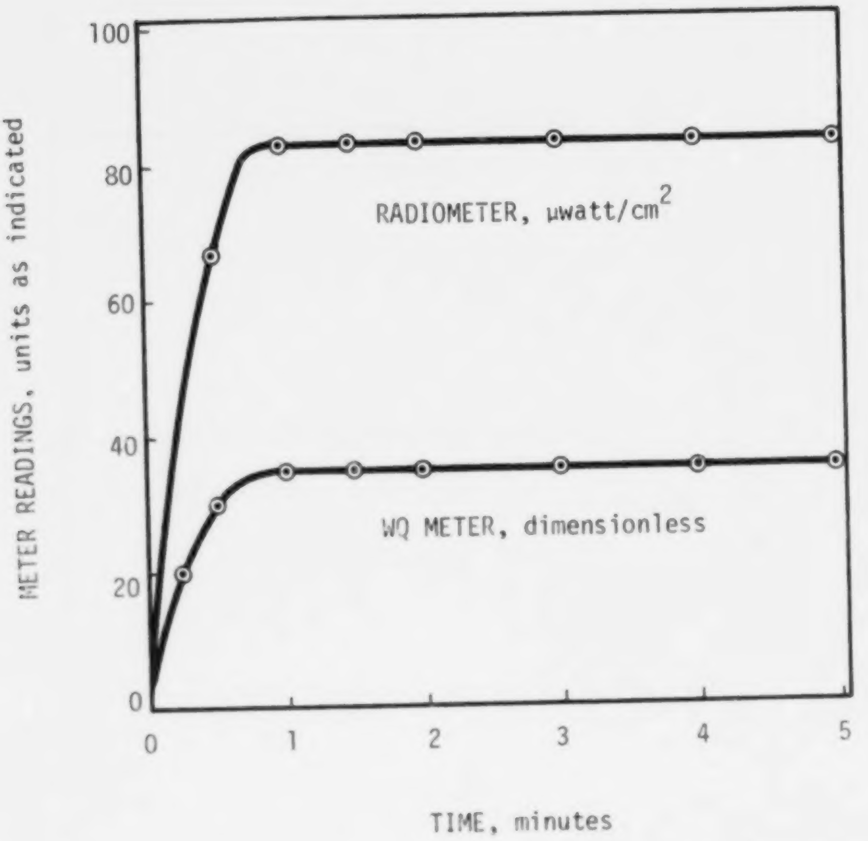


Figure 113. Meter readings after five minutes of purging with tap water.

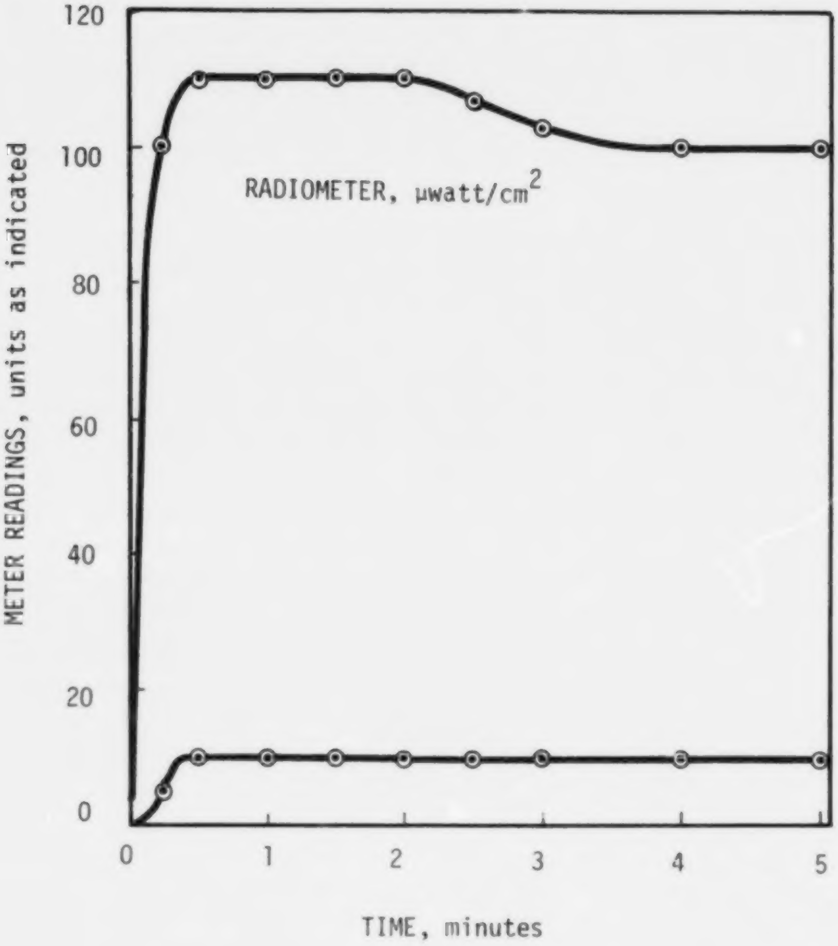


Figure 114. Meter Readings on activated sludge effluent.

disinfection unit was not adequately flushed after it was cleaned, the residual cleaning compound may have caused the low intensity readings. Another possibility is that the tap water might have contained some UV absorbing materials that the wastewater did not. Although this is improbable, it cannot be eliminated as a possibility since the percent transmittance of the tap water was not measured.

The second virus run commenced approximately one hour after the above intensity experiments. As in the first virus run sampling was done at four flow rates: 4.7, 0.6, 1.9, and 3.2 l/sec., respectively. The sampling protocol was not substantially different from the first run. The most significant changes involved the timing at the 0.6 l/sec flow rate which was to permit a sufficient amount of time to pass for flushing of the lines and UV unit.

A brief operating summary of the second virus run is presented in Table 41. Start and stop readings were noted on both the International Light radiometer and the UPS water quality meter. Analytical summaries of the chemical and bacteriological data follow on Tables 42 and 43. Some additional chemical analyses were performed on the initial and final influent samples (4.7 and 3.2 l/sec, respectively), including N-series, TDS, and chlorides. It is evident from Table 42 that there were no significant differences in the chemical characteristics between influent and effluent samples in the second virus run.

The data in Table 43 indicate that the total and fecal coliform log reductions were lower than in the first virus run, probably reflecting the effect of reduced ultraviolet dosages as determined by lower intensity measurements. It is difficult to determine the cause of the diminished UV intensity readings in the second virus run. Comparison of Table 42 and with Table 34 reveals that the only wastewater quality variable which increased in the second virus run was color. This may have been responsible for the decreased percent transmittance observed in the latter run. Another possibility, discussed earlier, was film build-up on the quartz sleeves surrounding the UV lamps, thereby partially attenuating the UV output from the lamps.

Results from the phage seeding experiments are given in Tables 44 and 45. It is clear from Table 44 that the displacement problem encountered with the control samples of the first virus run was resolved, since phage were present in all control samples. Moreover, steady-state flow conditions were established at all flow rates, since influent and effluent samples both contained comparable phage titers. It is evident from Table 45 that the titers of indigenous phage were negligible relative to the seeded samples. Results of exposing F2 phage to ultraviolet light indicated that the phage again were more resistant than total and fecal coliform bacteria.

Results from the poliovirus seeding experiments are summarized in Table 46. Steady-state flow conditions were established, as evidenced by the comparable virus titers between the influent and effluent control samples at each flow condition. Again, mean log reduction of poliovirus increased with detention time, as in the first virus run. It appears that poliovirus

TABLE 41. OPERATING SUMMARY OF SECOND UV VIRUS RUN

Flow (1/sec)	4.7	3.2	1.9	0.6
WQ Meter (start) Dimensionless Units (scale 0-40)	10	5	5	3
WQ Meter (finish) Dimensionless Units (scale 0-40)	10	5	2	4
Radiometer (start), $\mu w/cm^2$	93	97	97	97
Radiometer (finish), $\mu w/cm^2$	107	97	93	97

TABLE 42. RESULTS OF CHEMICAL ANALYSES OF GRAB SAMPLES AVERAGED OVER ALL FOUR FLOW RATES IN THE SECOND VIRUS RUN.

Parameter	Influent to UV	Effluent from UV
COD, mg/l	37.4	39.1
TOC, mg/l	12	13
SOC, mg/l	8	8
BOD, mg/l	14	9
TSS, mg/l	23	24
Turbidity, NTU	3.6	3.7
Color, Pt-Co Units	40	42
NH_3-N, mg/l	4.4	-
Org-N, mg/l	3.6	-
NO_2-N + NO_3-N, mg/l	0.8	-
NO_2-N, mg/l	0.11	-
pH	7.6	7.6
Sp. Cond.	782	782
Total Alk., mg/l	172	172
TDS, mg/l	481	-
Cl^-, mg/l	64	-
%Transmittance at 254 nm (as received)	59.3	65.6
%Transmittance at 254 nm (centrifuged)	58.7	67.6

TABLE 43. SUMMARY OF THE BACTERIOLOGICAL DATA FROM THE SECOND VIRUS RUN.

	Flow Rate, 1/sec							
Parameter	4.7		3.2		1.9		0.6	
	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
Total Coliforms per 100 ml	$1.7\text{x}10^{6}$	$1.1\text{x}10^{4}$	$1.4\text{x}10^{6}$	$2.0\text{x}10^{2}$	$7.9\text{x}10^{5}$	$2.3\text{x}10^{2}$	$1.3\text{x}10^{6}$	$7.0\text{x}10^{1}$
LOG REDUCTION	2.19		3.85		3.54		4.26	
Fecal Coliforms per 100 ml	$1.7\text{x}10^{5}$	$8.0\text{x}10^{2}$	$2.3\text{x}10^{5}$	$2.0\text{x}10^{2}$	$2.3\text{x}10^{5}$	$8.0\text{x}10^{1}$	$3.3\text{x}10^{5}$	$7.0\text{x}10^{1}$
LOG REDUCTION	2.33		3.06		3.46		3.67	

TABLE 44. STEADY-STATE TITERS OF F2 BACTERIOPHAGE CONTROLS IN FIRST VIRUS RUN.

	Phage Titers, pfu			
	Detention Time, sec (Flow rate, 1/sec)			
Sample	11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6)
Control 2-Before UV Unit				
30 sec	-	4.0×10^2	-	-
60 sec	2.0×10^2	2.4×10^3	2.8×10^3	-
90 sec	-	2.6×10^3	2.3×10^3	-
120 sec	-	-	-	1.4×10^3
Geometric Mean	2.0×10^2	1.4×10^3	2.5×10^3	1.4×10^3
Control 3-After UV Unit				
30 sec	-	6.0×10^2	-	-
60 sec	2.0×10^2	7.2×10^3	5.8×10^3	-
90 sec	-	9.0×10^2	1.6×10^3	-
120 sec	-	-	-	2.0×10^3
Geometric Mean	2.0×10^2	1.6×10^3	3.0×10^3	2.0×10^3
Control 1-Seed Culture				
Start 6.2×10^6				
End 8.0×10^6				

TABLE 45. TITERS OF F2 BACTERIOPHAGE EXPOSED TO ULTRAVIOLET RADIATION AT DIFFERENT FLOW RATES IN SECOND VIRUS RUN.

	Phage Titer, pfu/ml			
Detention Time (sec)	Detention Time, sec (Flow rate, l/sec)			
Flow (l/sec)	11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6)
INDIGENOUS PHAGE				
60 sec	6.2×10^{1}	4.0×10^{0}	1.2×10^{1}	8.0×10^{0}
120 sec	3.6×10^{1}	2.0×10^{0}	1.0×10^{1}	1.0×10^{1}
180 sec	1.8×10^{1}	2.0×10^{0}	6.0×10^{0}	1.0×10^{1}
Geometric Mean	3.4×10^{1}	2.5×10^{0}	9.0×10^{0}	9.3×10^{0}
Before UV Unit				
60 sec	9.0×10^{2}	5.0×10^{2}	1.2×10^{3}	1.2×10^{3}
120 sec	1.0×10^{3}	6.0×10^{2}	8.0×10^{2}	9.8×10^{2}
180 sec	1.2×10^{3}	2.0×10^{2}	1.8×10^{3}	3.2×10^{2}
Geometric Mean	1.0×10^{3}	3.9×10^{2}	1.2×10^{3}	7.2×10^{2}
After UV Unit				
60 sec	6.0×10^{0}	2.0×10^{0}	4.0×10^{0}	8.0×10^{0}
120 sec	1.0×10^{1}	1.9×10^{1}	1.0×10^{0}	8.0×10^{0}
180 sec	8.0×10^{0}	4.2×10^{1}	1.3×10^{1}	1.0×10^{1}
Geometric Mean	7.8×10^{0}	1.2×10^{1}	3.7×10^{0}	8.6×10^{0}
LOG REDUCTION	2.13	1.52	2.51	1.93

*Sampling Times for the 0.6 l/sec flow were 3 minutes, 4 minutes and 5 minutes.

TABLE 46. TITERS OF POLIOVIRUS TYPE I EXPOSED TO UV RADIATION AT DIFFERENT FLOW RATES IN SECOND VIRUS RUN.

Sample	Virus Titers, pfu/ml Detention Time, sec (Flow rate, l/sec) 11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (0.6*)
Control 2-Before UV				
30 sec	$5.9x10^3$	$6.7x10^3$	$8.8x10^3$	$2.6x10^4$
60 sec	$4.4x10^3$	$6.0x10^3$	$1.1x10^4$	$2.3x10^4$
90 sec	$4.6x10^3$	$6.9x10^3$	$7.6x10^3$	$2.0x10^4$
Geometric Mean	$4.9x10^3$	$6.5x10^3$	$8.9x10^3$	$2.3x10^4$
Control 3-After UV				
30 sec	$4.9x10^3$	$3.6x10^3$	$1.1x10^3$	$1.3x10^4$
60 sec	$5.2x10^3$	$6.5x10^3$	$5.8x10^3$	$1.9x10^4$
90 sec	$4.7x10^3$	$6.8x10^3$	$7.1x10^3$	$1.7x10^4$
Geometric Mean	$4.9x10^3$	$5.4x10^3$	$3.6x10^3$	$1.6x10^4$
Before UV Unit**				
0 sec	$5.3x10^3$	$5.4x10^3$	$1.0x10^4$	$1.5x10^4$
60 sec	$5.0x10^3$	$4.0x10^3$	$1.1x10^4$	$1.4x10^4$
120 sec	$4.8x10^3$	$3.6x10^3$	$6.5x10^3$	$1.3x10^4$
Geometric Mean	$5.0x10^3$	$4.3x10^3$	$9.0x10^3$	$1.4x10^4$
After UV Unit**				
0 sec	$7.0x10^1$	$2.5x10^1$	$1.6x10^1$	$3.0x10^1$
60 sec	$1.2x10^2$	$2.4x10^1$	$1.2x10^1$	$1.7x10^1$
120 sec	$1.3x10^2$	$2.6x10^1$	$1.4x10^1$	$7.0x10^0$
Geometric Mean	$1.0x10^2$	$2.5x10^1$	$1.4x10^1$	$1.5x10^1$
LOG REDUCTION		2.23	2.81	2.97

*The sampling times for C-2 and C-3 were 1, 2, and 3 minutes for this flow rate.

** U.V. lights had been on for two minutes.

Other results:

All samples from the Cl_2 contact basin were 0.

All samples for indigenous virus were 0.

Control 1 (virus feed): start = 4.0×10^7 PFU/ml
end = 2.95×10^7 PFU/ml

may have been slightly less responsive to UV than total and fecal coliforms during this run. A complete summary of the second virus run is given in Table 47.

A summary of the dose-related data is given in Table 48. Due to the much lower intensity readings, much lower indicated doses, D_I, were observed. Contrary to the first virus run the theoretical dosages were a good approximation of the indicated dosages.

THIRD UV VIRUS RUN

The third programmed UV virus run with the UPS Ultraviolet Disinfection Unit was performed on the morning of 26 June 1975. Preparations for the run began on 24 June when the unit was taken out of service and cleaned with UPS cleaning solution. After draining the unit, fresh cleaning solution was added and allowed to recirculate through the contactor all night by means of a small externally-mounted booster pump. Early on the morning of 25 June, the cleaning solution was flushed with tap water, and the radiometer reading was 760 μwatt/cm^2. However, the reading fell to 20 μwatts/cm^2 following introduction of activated sludge effluent to the unit.

It was originally planned to conduct the virus run on the 25th; however, in view of the UV intensity on that morning it was decided to postpone the run until the next day, and the cleaning sequence was repeated. Although the poliovirus stock culture had been thawed by the time this decision was made, the F2 phage had not been added. The virus solution was stored overnight at 5^{o}C, and F2 phage were added to it on the morning of 26 June.

Performance of the demonstration plant was monitored very closely prior to the run. Grab samples of activated sludge effluent were taken at 11 AM, 1:30 PM, and 3:35 PM on 25 June for COD analyses. The results were: 122, 124, and 129 mg/l COD, respectively. Average DO in the aeration basin was 1.2 mg/l in spite of efforts to increase it. On 26 June, the day of the run, the same average DO was measured. MLVSS was 2170 mg/l. SVI was 306 mg/l. The F/M ratio was 0.34 kg COD/day-kg MLSS. The aeration rate was 0.48 m^3/m^3. -- more than adequate for the high rate operating mode with good oxygen transfer equipment.

On the morning of 26 June the virus run commenced, in spite of the fact that the initial radiometer reading on activated sludge effluent was only 30 μwatt/cm^2. The process configuration and operating protocol were identical to the second virus run. Start-finish meter readings at each of the four flow rates are listed on Table 49. The lowest UV intensity measured by the IL 500 radiometer was 26 μwatt/cm^2. The highest was 29 μwatt/cm^2.

Analytical results of the chemical analyses are presented in Table 50. It is clear that the influent wastewater quality for the third virus run had substantially deteriorated. Although the level of TSS was similar to the first two virus runs, organic matter in the form of COD, TOC, and BOD was

TABLE 47. SUMMARY OF RESULTS FROM SECOND VIRUS RUN

Organism	MEAN LOG REDUCTIONS Detention Time, sec (Flow rate, 1/sec) 11.4 (4.7)	 16.8 (3.2)	 28 (1.9)	 85 (0.6)
Total Coliforms	2.19	3.85	3.54	4.26
Fecal Coliforms	2.33	3.06	3.46	3.67
F_2 Bacteriophage	2.13	1.52	2.51	1.93
Poliovirus Type 1	1.69	2.23	2.81	2.97

TABLE 48. SUMMARY OF DOSE RELATED DATA FOR THE SECOND VIRUS RUN

Flow rate, l/sec	4.7	3.2	1.9	0.6
Theoretical Detention Time, sec	11.4	16.8	28.2	85.1
Actual Detention Time, sec	10	15.5	25	75
Transmittance @ 254 nm, percent	62.5	62.5	62.5	62.5
Extinction Coefficient, cm^{-1}	0.48	0.48	0.48	0.48
UV Intensity, μwatt/cm^2	100	97	95	97
Calculated Dose, D_T, μwatt-sec/cm^2	8,500	12,500	20,900	63,100
Indicated Dose, D_I, μwatt-sec/cm^2	8,900	13,400	21,100	64,700

TABLE 49. SUMMARY OF OPERATIONS OF VIRUS RUN NO. 3

Flow (l/sec)	4.7	3.2	1.9	0.6
WQ Meter (start)	0	0	0	0
WQ Meter (finish)	-	0	0	0
Radiometer (start), μw/cm^2	26	29	29	29
Radiometer (finish), μw/cm^2	-	28.5	27	26.5

TABLE 50. RESULTS OF CHEMICAL ANALYSES OF GRAB SAMPLES AVERAGED OVER ALL FOUR FLOW RATES IN THE THIRD VIRUS RUN.

Parameter	Influent to UV	Effluent from UV
COD, mg/l	75.2	77.0
TOC, mg/l	28	30
SOC, mg/l	11	12
BOD, mg/l	22	15
TSS, mg/l	22	23
Turbidity, NTU	11	11
Color, Pt-Co Units (filtered)	30	30
NH_3-N, mg/l	10.3	-
Org.-N, mg/l	6.2	-
NO_2-N + NO_3-N, mg/l	0.3	-
NO_2-N, mg/l	0.05	-
pH	7.6	7.5
Sp. Cond.	900	900
Total Alk., mg/l	182	184
TDS, mg/l	436	-
Cl^-, mg/l	70	-
%Transmittance at 254 nm	51.6	51.6

almost double previous levels. NH_3-N and organic-N were markedly higher, and UV transmittance was significantly lower. Turbidity was three times higher than previous runs.

Results of the microbiological samples are given in Table 51. Influent MPN's were 1 to 2 logs higher than other virus runs, again reflecting the generally deteriorated wastewater quality conditions. Log coliform reduction were substantially lower and more erratic.

Results of the control sampling for F2 phage are shown in Table 52. The influent controls in the 4.7, 1.9, and 0.6 l/sec. runs were close to the expected values.

The respective effluent controls, however, were significantly lower. The only explanation which can be offered is the generally poorer wastewater quality, which may have adversely affected phage survival and recovery. Results from exposing the seeded phage to ultraviolet disinfection are given in Table 53. It is evident that the titers of indigenous phage were not insignificant relative to the seeded numbers. Thus when evaluating the log reduction values, it is difficult to ascertain which phage population contributed more to the effect. In general, the log reductions were lower and more erratic than in previous runs.

Table 54 presents the results of the poliovirus analyses of the third virus run. As can be seen the effluent counts were higher than the previous two runs. This was clearly due to the substantially reduced UV dosage as a result of the marked attenuation of the UV energy by the poorer quality wastewater. Examination of the results of the control samples before and after the UV unit indicates that steady-state conditions were readily achieved. A complete summary of the third virus run is given in Table 55.

Table 56 summarizes the dose-related data for the third virus run. The dosages obtained in this run were much lower than the other two runs. This is also evident in the disinfection data, since the worst disinfection occurred during the third virus run.

Figures 115-118 summarize the microorganism reduction data from the three virus runs. The runs were made during a period of equipment difficulties when effluent COD values ranged from 37 to 75 mg/l. The highest COD waters gave the poorest microbiological results, but little difference was observed between phages and poliovirus. The phages were possibly a little more resistant than the poliovirus, and the fecal coliforms were a little more resistant than both the viruses, but the equations are really not that different particularly in view of the low correlation coefficients (0.70-0.72). Figures 116 and 117 show the individual data points and resultant curve for fecal coliforms and coliphages, respectively, and Figure 118 compares the curves for both these organisms with that of polio. The no-effect dose (determined by settling $y = o$ and solving for x) ranges from 148 μ watt-sec/cm^2 for fecal coliforms to 871 μ watt-sec/cm^2 for coliphages.

TABLE 51. SUMMARY OF THE BACTERIOLOGICAL DATA FROM THE THIRD VIRUS RUN.

	Flow Rate, 1/sec							
	4.7		3.2		1.9		0.6	
Parameter	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
Total Coliforms per 100 ml	$5.4x10^7$	$>2.4x10^5$	$3.5x10^6$	$>2.4x10^5$	$>2.4x10^8$	$9.2x10^4$	$>2.4x10^8$	$>2.4x10^5$
LOG REDUCTION	<2.35		<1.16		3.42		<3.00	
Fecal Coliforms per 100 mo	$1.3x10^7$	$1.7x10^4$	$1.7x10^6$	$9.2x10^4$	$1.7x10^7$	$1.1x10^4$	$4.9x10^6$	$1.1x10^4$
LOG REDUCTION	2.88		1.27		3.19		2.65	

TABLE 52. STEADY-STATE TITERS OF F_2 BACTERIOPHAGE CONTROLS IN THIRD VIRUS RUN.

	Phage Titers, pfu/ml			
	Detention Time, sec (Flow rate, l/sec)			
Sample	11.2 (4.7)	16.8 (3.4)	28 (1.9)	84 (0.6*)
Control 2-Before UV Unit				
30 sec	1.8×10^3	6.5×10^2	3.3×10^3	8.3×10^4
60 sec	1.0×10^3	6.5×10^2	4.6×10^3	8.5×10^4
90 sec	1.0×10^3	3.7×10^2	4.1×10^3	1.0×10^4
Geometric Mean	1.2×10^3	5.4×10^2	4.0×10^3	4.1×10^4
Control 3-After UV Unit				
30 sec	1.6×10^2	3.2×10^2	6.0×10^2	2.2×10^3
60 sec	2.2×10^2	1.6×10^2	**	2.8×10^3
90 sec	2.2×10^2	1.8×10^2	4.0×10^2	1.8×10^3
Geometric Mean	2.0×10^2	2.1×10^2	4.9×10^2	2.2×10^3
Control 1-SEED CULTURE				
Start 4.6×10^6				
End 2.6×10^6				

*Sampling on the 0.6 l/sec flow was performed at 1 minute, 2 minutes, and 3 minutes.

** Data not available.

TABLE 53. TITERS OF F_2 BACTERIOPHAGE EXPOSED TO ULTRAVIOLET RADIATION AT DIFFERENT FLOW RATES IN THIRD VIRUS RUN.

Sample	Phage Titers, pfu/ml			
	Detention Time, sec (Flow Rates, l/sec)			
	11.2 (4.7)	16.8 (3.2)	28 (1.9)	84 (0.6*)
INDIGENOUS PHAGE				
60 sec	4.4×10^{2}	3.6×10^{2}	1.3×10^{2}	2.2×10^{2}
120 sec	3.9×10^{2}	1.4×10^{2}	1.9×10^{2}	2.4×10^{2}
180 sec	2.1×10^{2}	2.0×10^{2}	5.0×10^{1}	4.6×10^{2}
Geometric Mean	3.3×10^{2}	2.2×10^{2}	1.1×10^{2}	2.9×10^{2}
Before UV Unit				
60 sec	1.4×10^{3}	7.1×10^{2}	2.0×10^{2}	3.0×10^{3}
120 sec	1.5×10^{3}	1.4×10^{3}	3.0×10^{2}	2.1×10^{3}
180 sec	4.6×10^{2}	1.1×10^{3}	6.0×10^{2}	2.5×10^{3}
Geometric Mean	9.9×10^{2}	1.0×10^{3}	3.3×10^{2}	2.5×10^{3}
After UV Unit				
60 sec	7.4×10^{1}	$<1.0\times10^{1}$	1.0×10^{1}	8.0×10^{1}
120 sec	1.2×10^{2}	6.0×10^{1}	2.0×10^{1}	1.8×10^{1}
180 sec	8.7×10^{1}	2.0×10^{1}	4.0×10^{0}	1.8×10^{1}
Geometric Mean	9.2×10^{1}	$<2.3\times10^{1}$	9.3×10^{0}	3.0×10^{1}
LOG REDUCTION	1.04	>1.64	1.55	1.92

*Sampling for the 0.6 l/sec flow was performed at 3 min, 4 min, and 5 min.

TABLE 54. TITERS OF POLIOVIRUS TYPE I EXPOSED TO UV RADIATION AT DIFFERENT FLOW RATES IN THIRD VIRUS RUN.

	Virus Titers, pfu/ml			
	Detention Time, sec (Flow Rate, l/sec)			
Sample	11.2 (4.7)	16.8 (3.2)	28 (1.9)	84 (0.6*)
Control 2-Before UV Unit				
30 sec	6.7×10^{3}	5.2×10^{3}	1.5×10^{4}	5.9×10^{4}
60 sec	8.5×10^{3}	7.6×10^{3}	1.6×10^{4}	6.2×10^{4}
90 sec	6.6×10^{3}	7.9×10^{3}	1.6×10^{4}	8.0×10^{4}
Geometric Mean	7.2×10^{3}	6.8×10^{3}	1.6×10^{4}	6.6×10^{4}
Control 3-After UV Unit				
30 sec	6.8×10^{3}	7.3×10^{3}	1.6×10^{4}	2.5×10^{4}
60 sec	7.0×10^{3}	9.1×10^{3}	1.4×10^{4}	3.6×10^{4}
90 sec	4.3×10^{3}	7.2×10^{3}	1.7×10^{4}	5.3×10^{4}
Geometric Mean	5.9×10^{3}	7.8×10^{3}	1.5×10^{4}	3.6×10^{4}
Before UV**				
0 sec	6.1×10^{3}	9.6×10^{3}	1.5×10^{4}	7.1×10^{4}
60 sec	7.2×10^{3}	6.9×10^{3}	1.9×10^{4}	4.3×10^{4}
120 sec	5.3×10^{3}	7.5×10^{3}	1.5×10^{4}	6.1×10^{4}
Geometric Mean	6.2×10^{3}	7.9×10^{3}	1.6×10^{4}	5.7×10^{4}
After UV**				
0 sec	4.2×10^{2}	1.3×10^{2}	1.5×10^{2}	3.3×10^{2}
60 sec	5.1×10^{2}	1.3×10^{2}	1.4×10^{2}	1.3×10^{2}
120 sec	7.5×10^{2}	2.2×10^{2}	1.7×10^{2}	1.3×10^{2}
Geometric Mean	5.4×10^{2}	1.5×10^{2}	1.5×10^{2}	1.8×10^{2}
Log Reduction	1.06	1.72	2.02	2.50

*The sampling Time for 0.6 l/sec flow was 1 min, 2 min, and 3 min.

**The UV lights had been on for 2 minutes.

Other Results:
All samples from the Cl_2 contact basin were <1.
All samples for indigenous virus were <1.
Control 1 (virus feed); Start 7.55×10^{7} PFU/ml
8.45×10^{7} PFU/ml

TABLE 55. SUMMARY OF RESULTS FROM THIRD VIRUS RUN.

	MEAN LOG REDUCTIONS			
	Detention Time, sec. (Flow Rate, 1/sec.)			
Organism	11.4 (4.7)	16.8 (3.2)	28 (1.9)	85 (1.9)
Total Coliforms	<2.35	<1.16	3.42	<3.00
Fecal Coliforms	2.88	1.27	3.19	2.65
F2 Bacteriophage	1.04	>1.64	1.55	1.92
Poliovirus Type 1	1.06	1.72	2.02	2.50

TABLE 56. SUMMARY OF DOSE-RELATED DATA FOR THE THIRD VIRUS RUN

Flow Rate, l/sec	4.7	3.2	1.9	0.6
Theoretical Detention Time, sec	11.4	16.8	28.2	85.1
Actual Detention Time, sec	10	15.5	25	75
Transmittance @ 254 nm, percent	51.6	51.6	51.6	51.6
Extinction Coefficient, cm^{-1}	0.65	0.65	0.65	0.65
UV Intensity, $\mu watt/cm^2$	26	29	28	28
Calculated Dose, D_T, $\mu watt\text{-}sec/cm^2$	4,300	6,300	10,600	32,000
Indicated Dose, D_I $\mu watt\text{-}sec/cm^2$	2,300	4,000	6,200	18,700

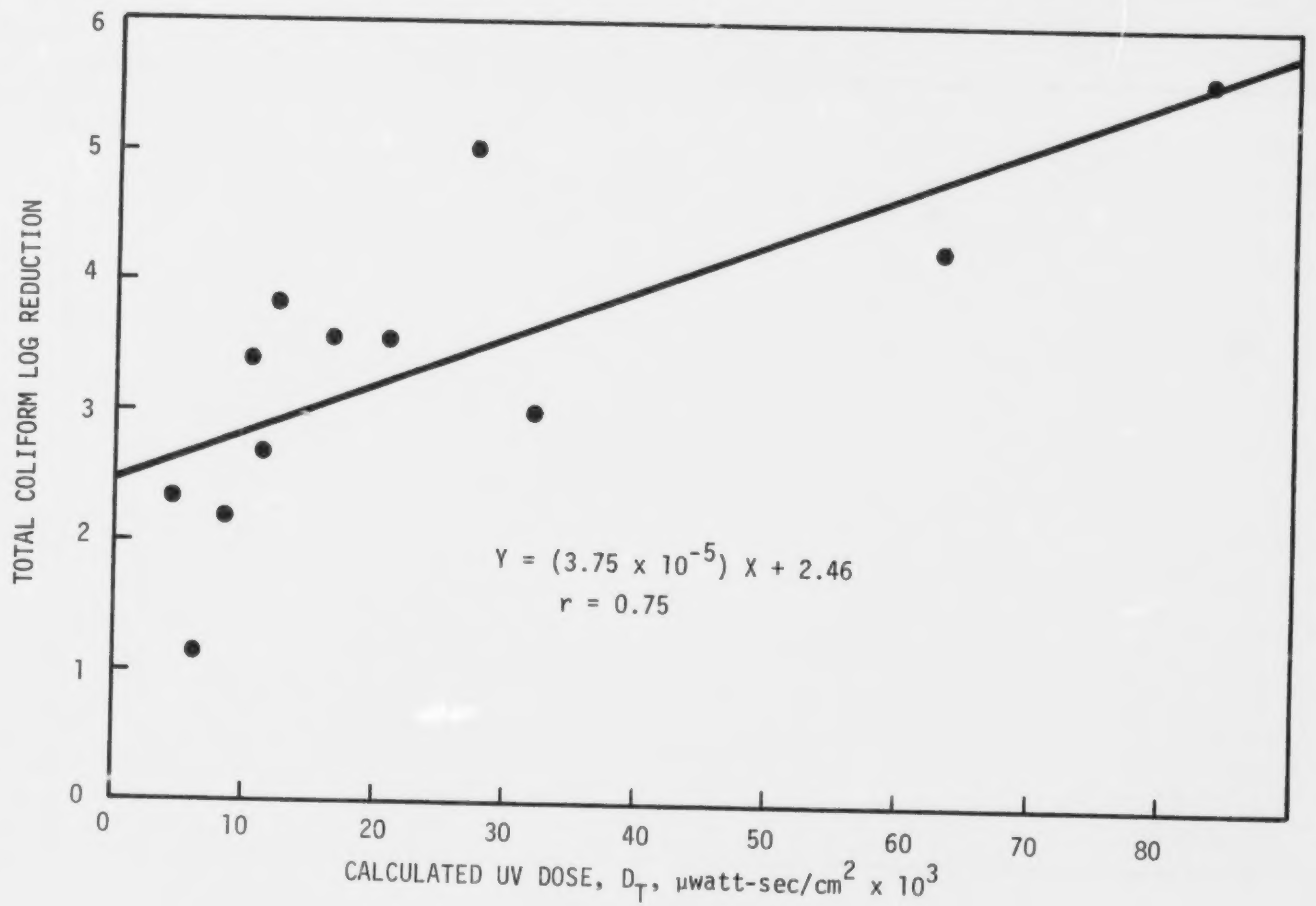


Figure 115. Total coliform log reduction as a function of the calculated dose.

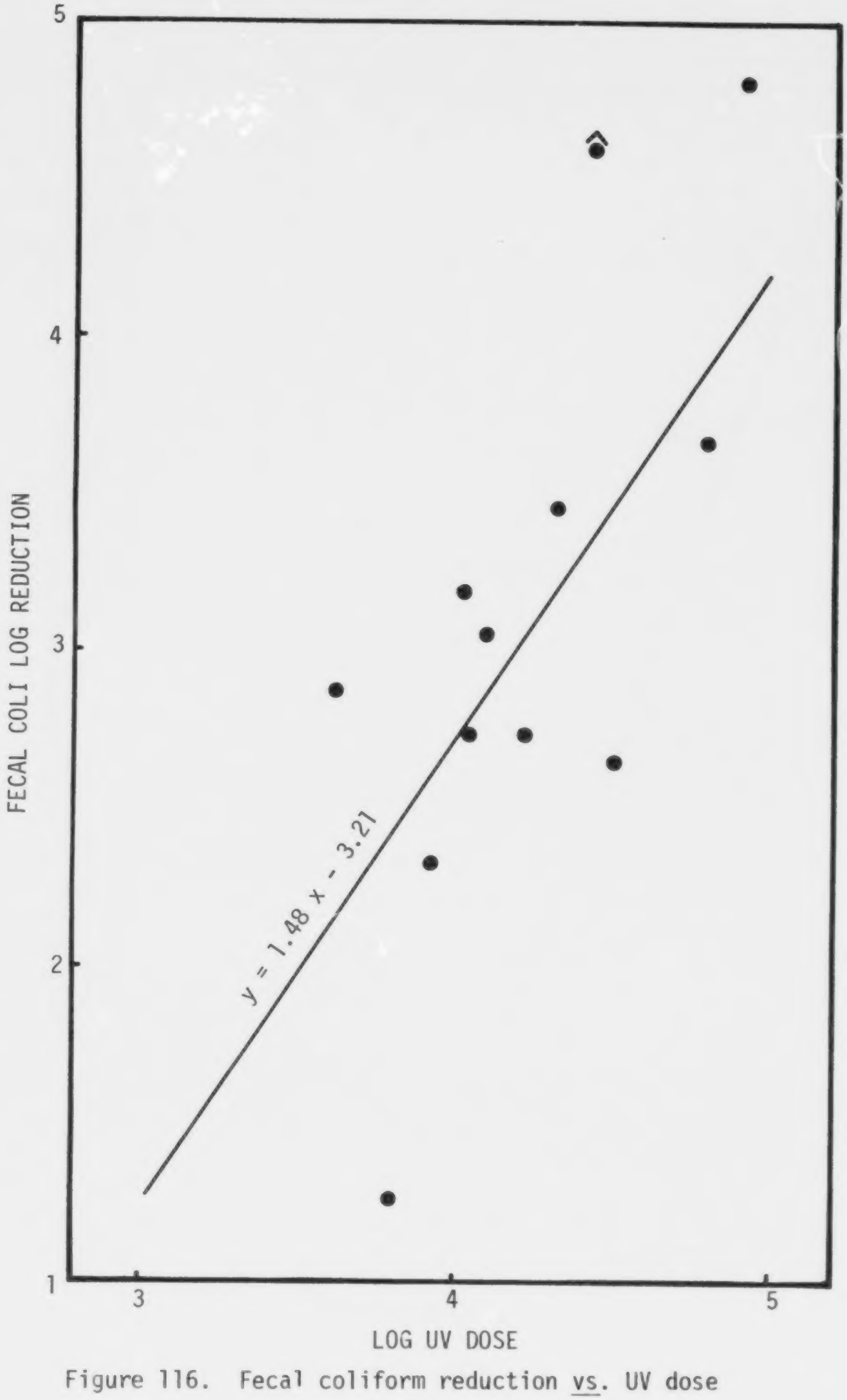


Figure 116. Fecal coliform reduction vs. UV dose

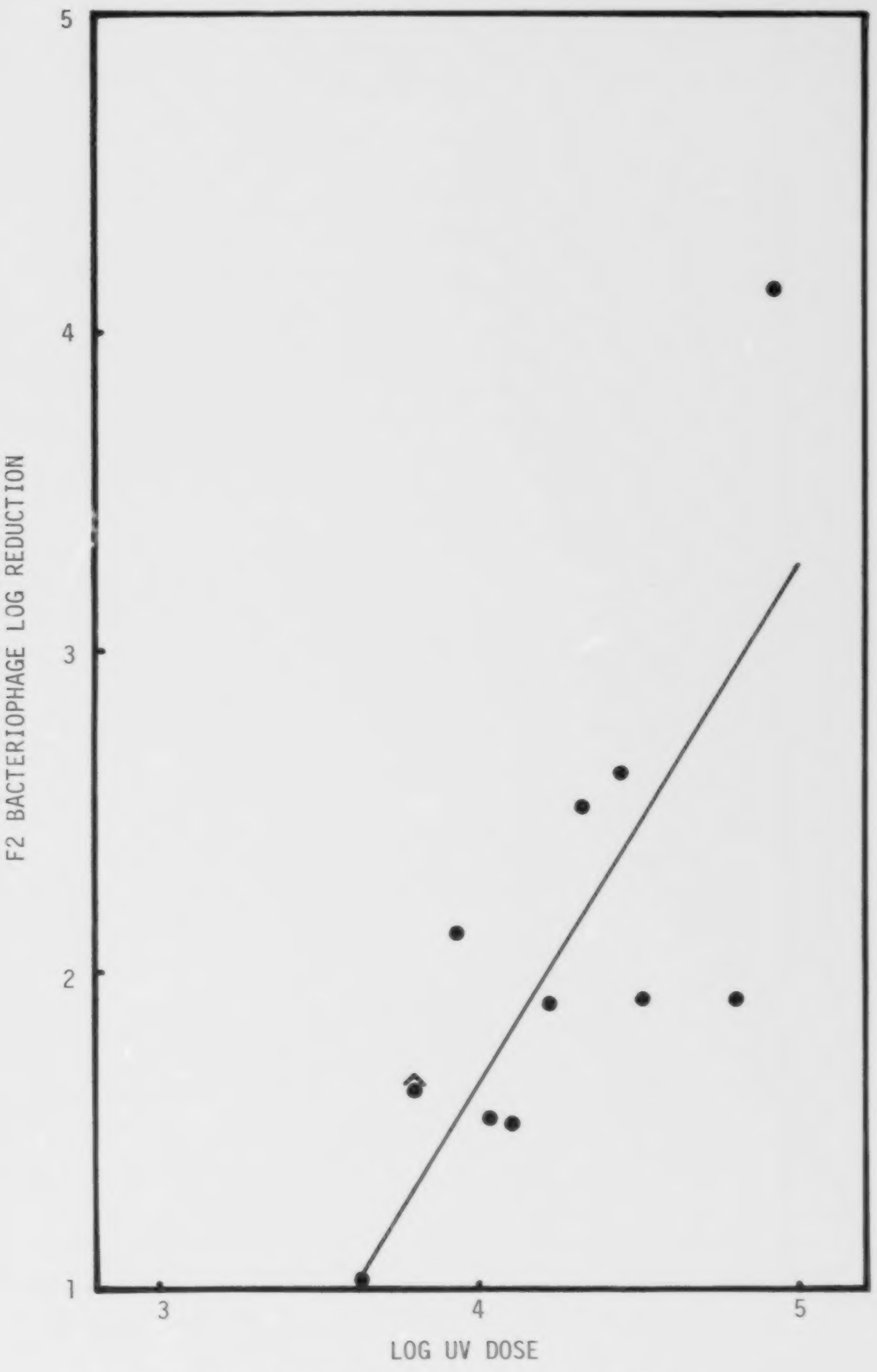


Figure 117. Coliphage reduction vs. UV dose

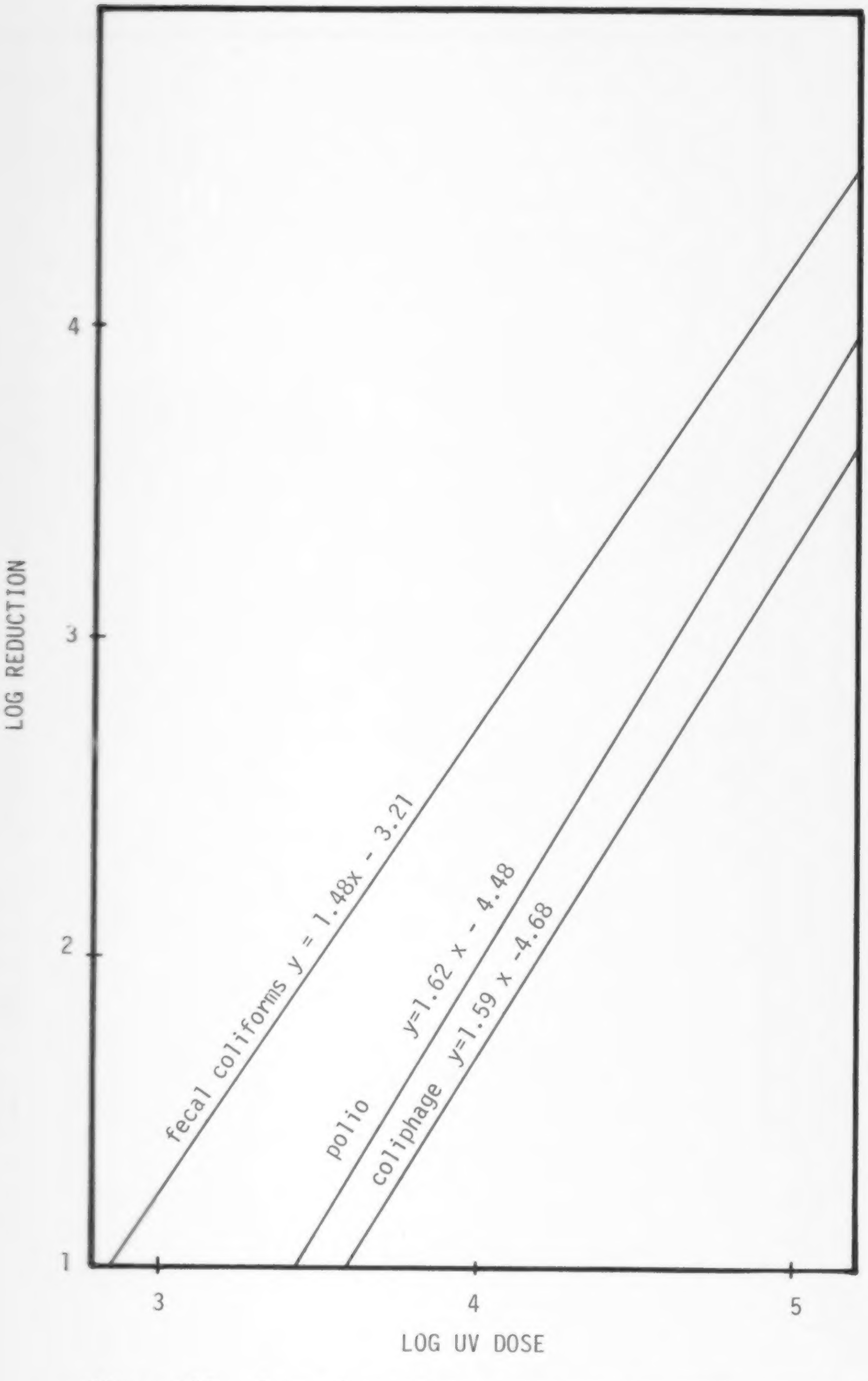


Figure 118. Comparison of dose-response for three organisms

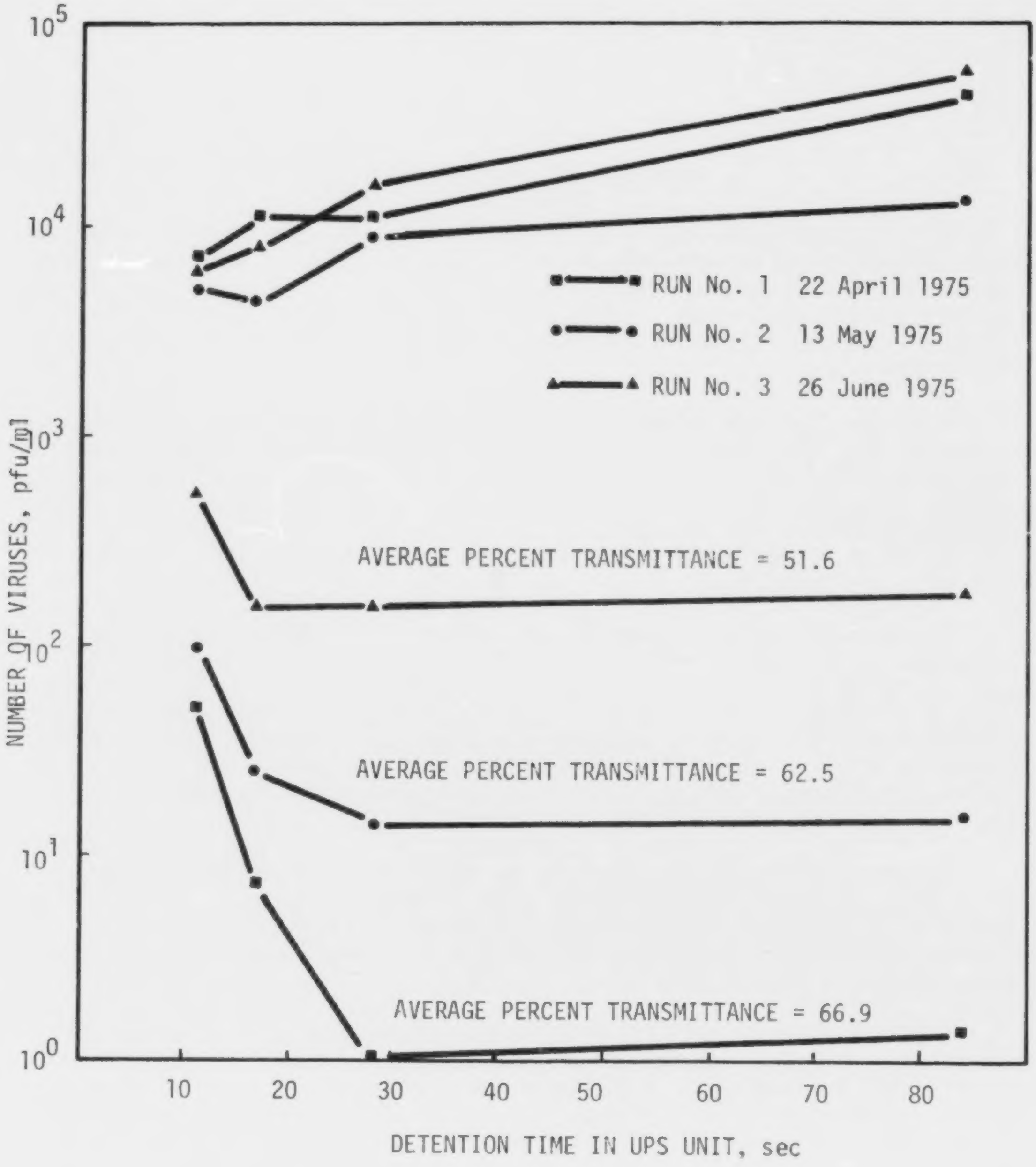


Figure 119. Virus reduction versus detention time.

SECTION 9

SUMMARY OF OPERATING EXPERIENCE

During the sixteen months in which the ultraviolet disinfection project was conducted an extensive amount of data was collected. It would be quite impossible to present the results of every analytical test performed during the project in this report. In this section the authors would like to summarize and review some of the more significant observations made during this research effort.

Previous data have shown that UV dose is the controlling factor in microorganism kill, and that the percent transmittance at 254 nm is very important to the actual dose received by the microorganisms in the exposure chamber (13, 14). At the start of this project, we expected UV transmission to be dependent on the turbidity of the water. The data presented in Figure 120, which is a plot of turbidity versus percent transmittance, indicate lack of correlation.

There would similarly seem to be a potential relationship between suspended solids and transmittance at 254 nm. Figure 121 presents these data (averages for each of the UPS runs), and correlation is clearly lacking, since a correlation coefficient of only 0.16 resulted. Additional efforts to improve on these data by plotting daily values, instead of run averages, proved fruitless. There does not appear to be any correlation between TSS and transmittance at 254 nm, at least within the ranges observed on the project.

Attempts were made to correlate the observed transmittance values, which were available only after the start of the UPS unit, and several additional water quality parameters. There is no correlation evident between either total phosphorus or combined nitrite-nitrate nitrogen and transmittance.

Figure 122 is a plot of percent transmittance versus the COD of the water being processed by the UPS disinfection unit. The correlation coefficient obtained was - 0.76, which is good for an experiment of this type. Transmittance is plotted as a function of total organic carbon in Figure 123. The correlation coefficient is - 0.95, which indicates very good correlation. The fact that COD and TOC correlate well with the observed transmissibility at 254 nm indicates that the amount of soluble organic material present in a wastewater will affect the efficiency of an ultraviolet light disinfection process used to treat that wastewater.

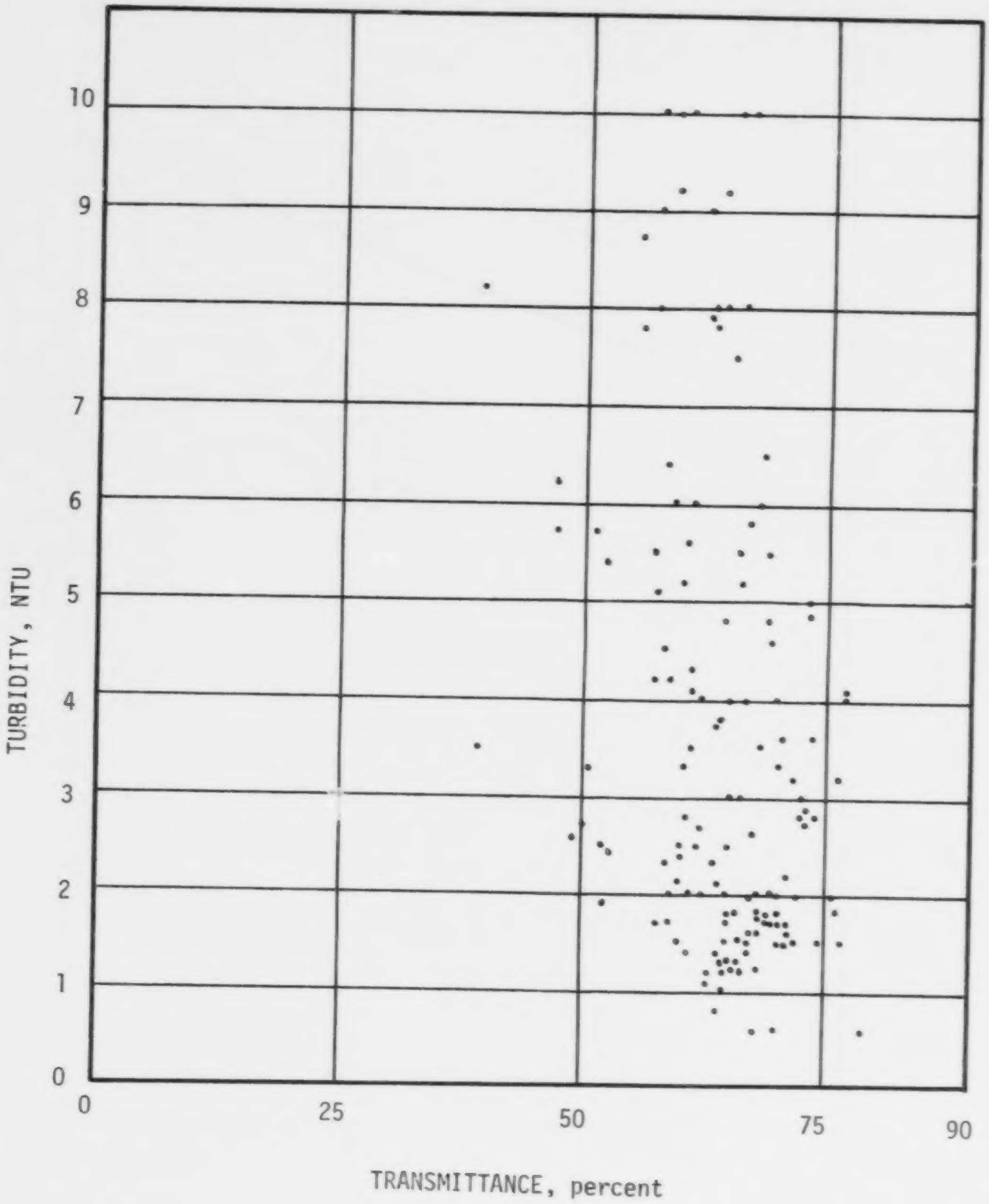


Figure 120. The effect of turbidity on percent transmittance.

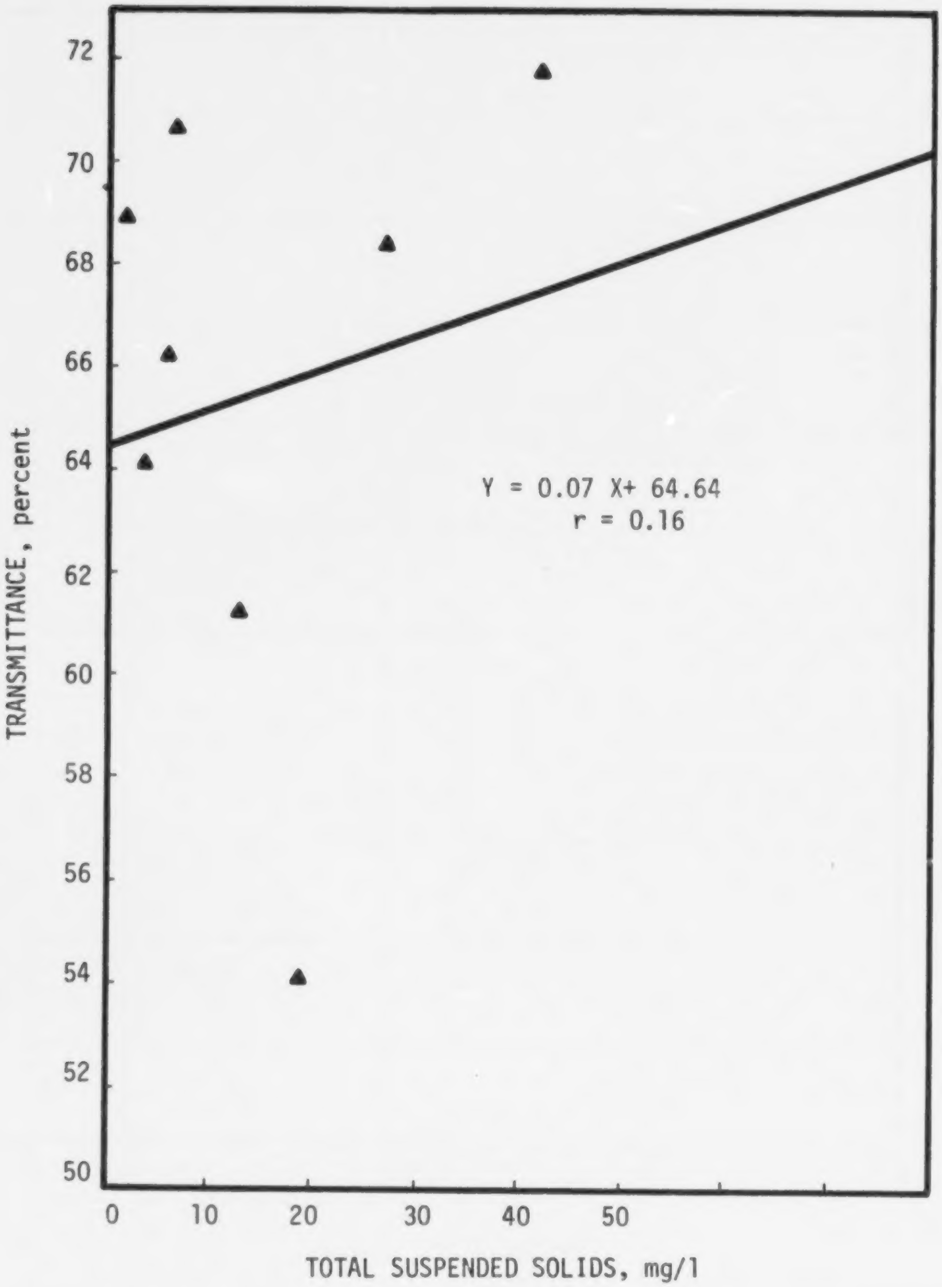


Figure 121. Correlation between percent Transmittance and Total Suspended Solids.

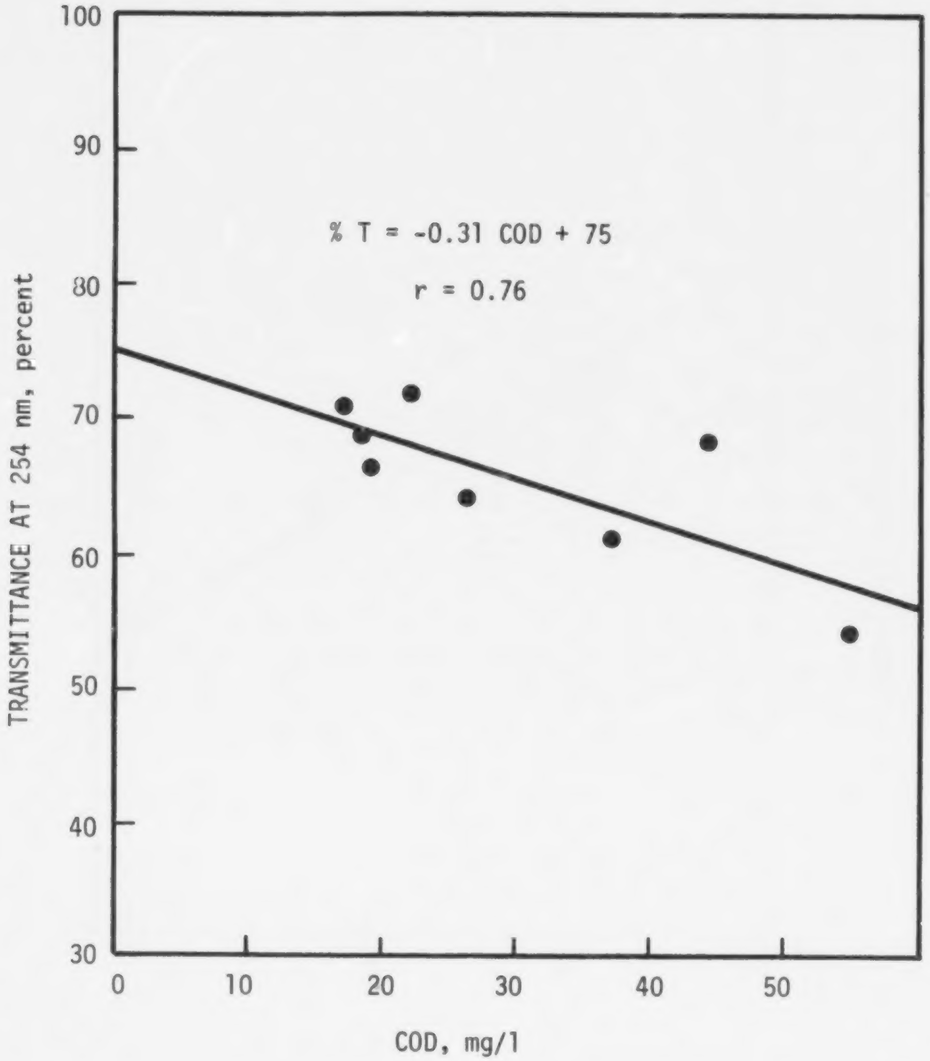


Figure 122. Correlation between transmittance at 254 nm and COD.

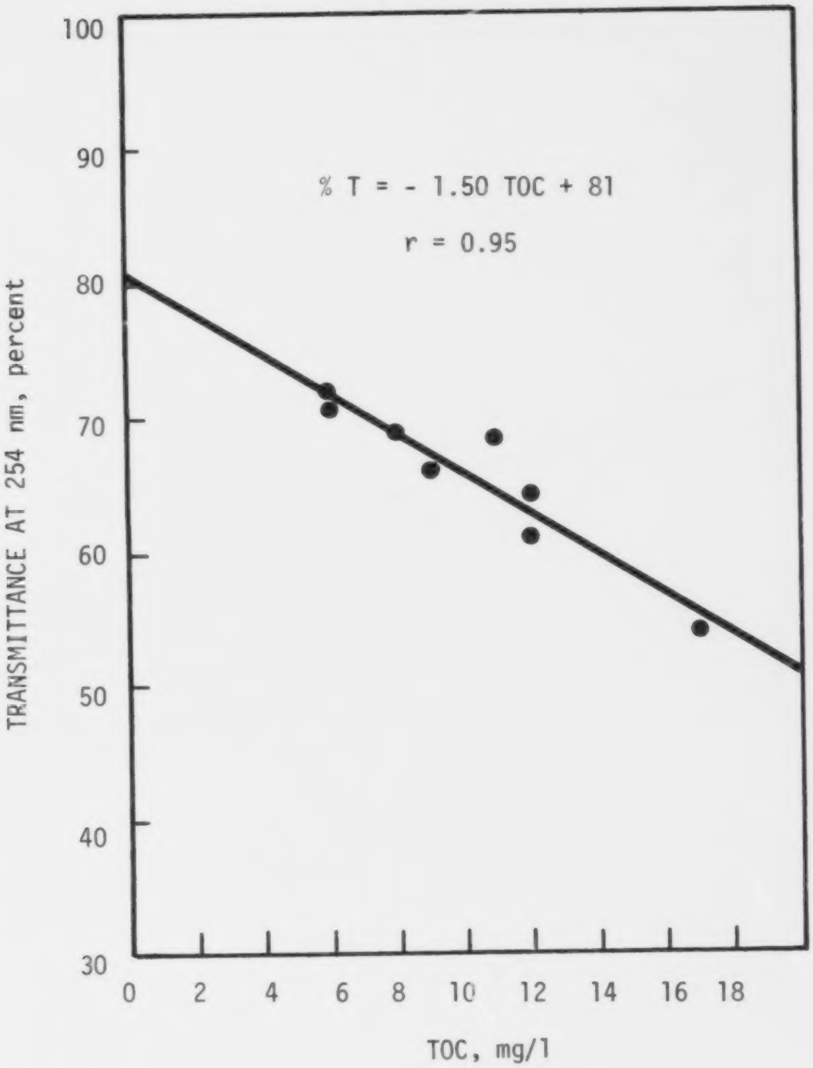


Figure 123. Correlation between transmittance at 254 nm and TOC.

The amount of organic material present in the effluent of a biological treatment process is related to the degree of nitrification occurring; therefore, a well-nitrified effluent should be more amenable to disinfection with ultraviolet light than a non-nitrified effluent. In Figure 124 ammonia-nitrogen concentrations are plotted as a function of both COD and TOC. The correlation coefficient for the NH_3-N versus TOC plot is 0.88, while the NH_3-N versus COD graph yields a correlation coefficient of 0.97. Both correlations are excellent, and indicate that reduced concentrations of organic compounds can be achieved by utilizing a nitrifying activated sludge system.

Since both COD and TOC correlated well with transmittance, a correlation between transmittance and the concentration of unoxidized nitrogen compounds was anticipated. Figure 125 is a plot of transmittance as a function of ammonia-N concentration. The correlation is quite good ($r = -0.81$), as is the correlation between organic nitrogen and transmittance ($r = -0.77$) shown in Figure 126.

The quartz sleeves housing the UV lamps in the UPS unit were subject to a certain amount of slime build-up since they were continuously submerged in a secondary effluent. Slime accumulation will decrease the amount of UV energy radiated to the surrounding water resulting in a decrease in the unit's disinfection efficiency. Figure 127 is a time series plot of the UV dose calculated from intensity readings. There is clearly a decrease in the UV dose, but the initial rate of decrease observed in early October is quite gradual. The rate of decrease observed in early November was considerably greater than the October rate. These data indicate that the sleeves remained clean for several weeks before significant slime development occurs but that the slime will accumulate rapidly once started.

The UPS unit was cleaned with a proprietary compound provided by Ultraviolet Purification Systems, Inc. in mid-November, and the UV dose increased to the early October values. The cleaning frequency required to keep the system operating at peak efficiency can be expected to vary with the quality of the effluent, but intervals of about two weeks seem reasonably consistent with these data and temperatures.

At the start of this project the factors expected to be responsible for the number of organisms found in the effluent from a UV disinfection system were total suspended solids, turbidity, transmissability at 254 nm, and UV dose, among others. Figure 128 is a graph of effluent total suspended solids versus effluent fecal coliforms. No readily apparent correlation exists between these two data sets, or the correspondence is only poorly defined. Attempts to quantify the suspected correlation between TSS and coliform densities were unsuccessful. Plots using data at a constant dose for any given run exhibited considerable scatter.

Figure 129 is a graph of effluent fecal coliforms versus turbidity, and no significant interdependence is evident. The fact that neither turbidity nor suspended solids have any demonstrated significant impact on the observed effluent fecal coliform counts is a significant finding, expecially

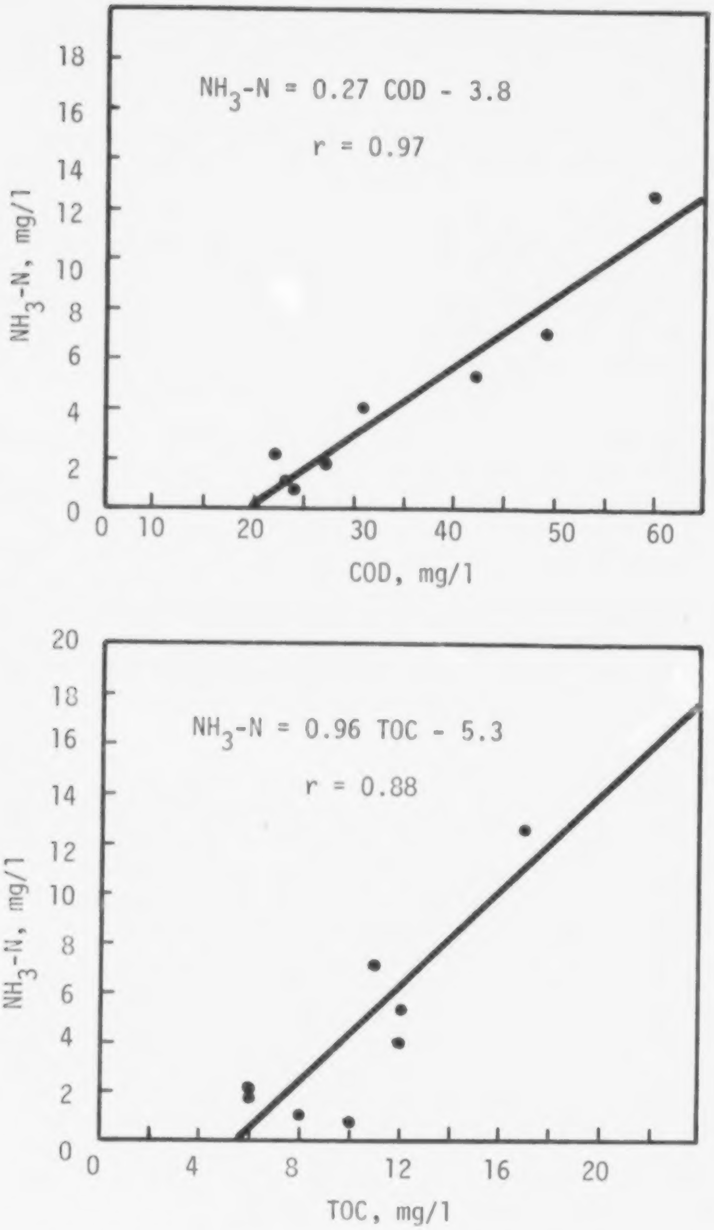


Figure 124. Correlations between ammonia-N and COD and TOC.

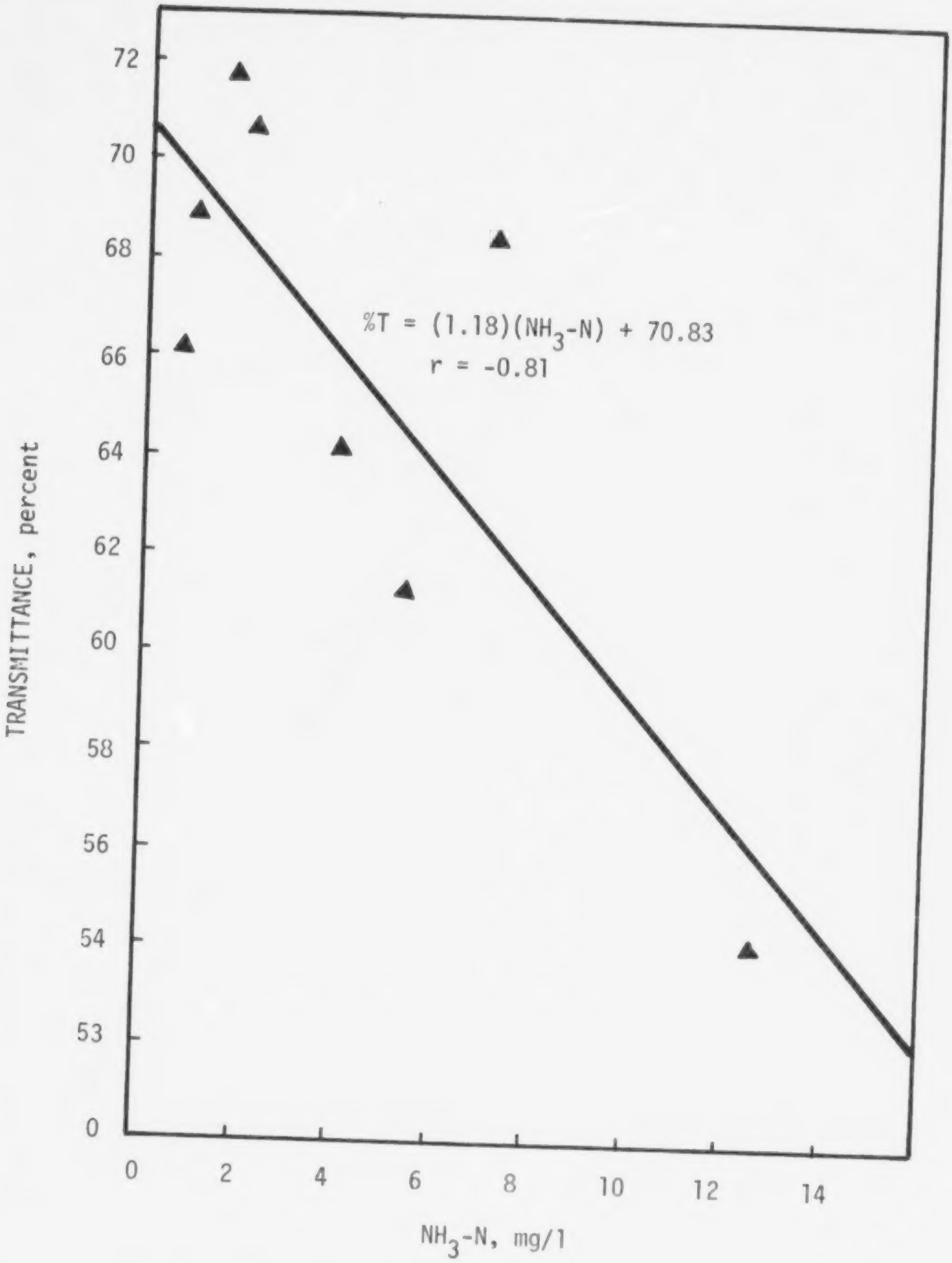


Figure 125. Correlation between NH_3-N and percent transmittance at 254 nm.

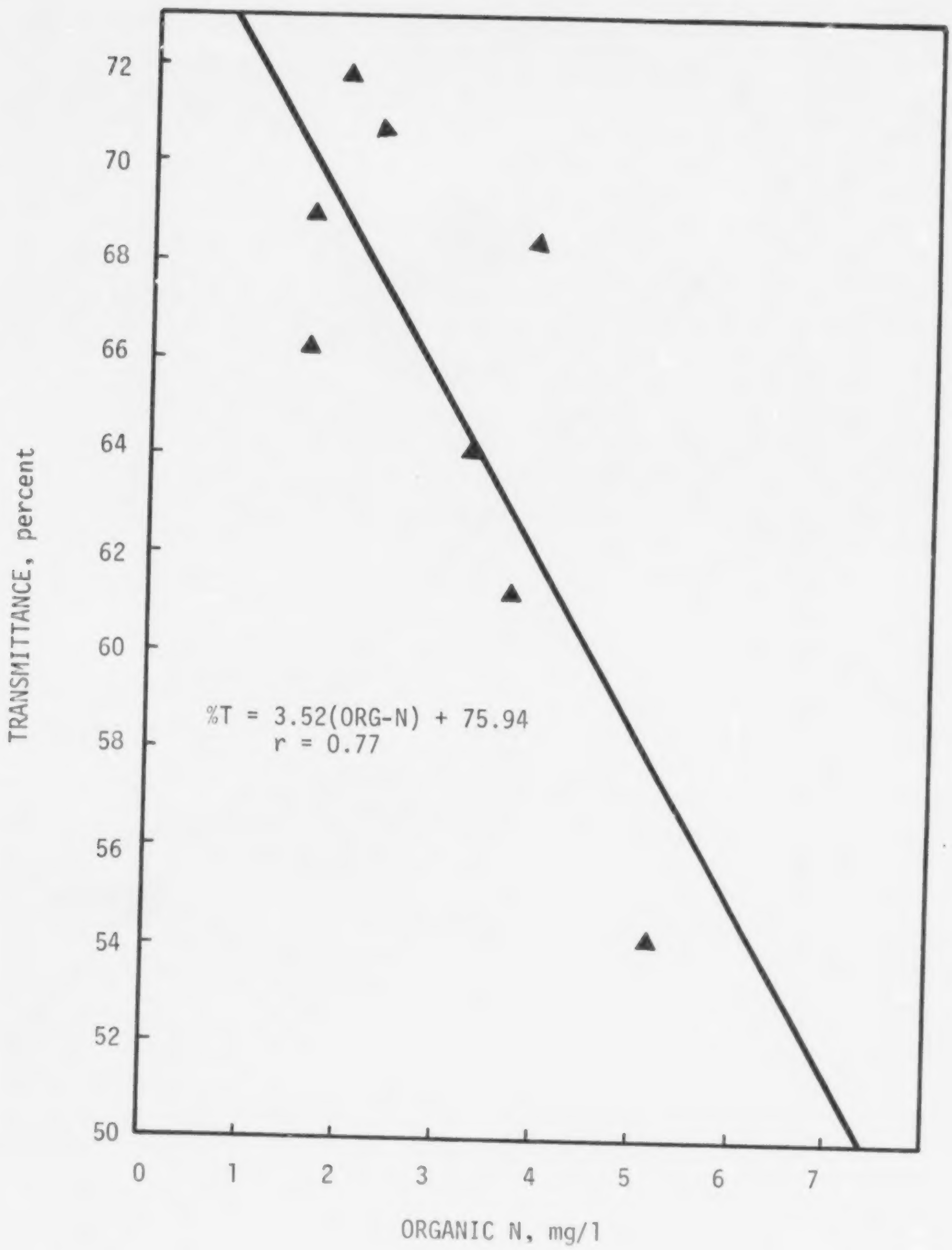


Figure 126. Correlation between organic nitrogen and percent transmittance at 254 nm.

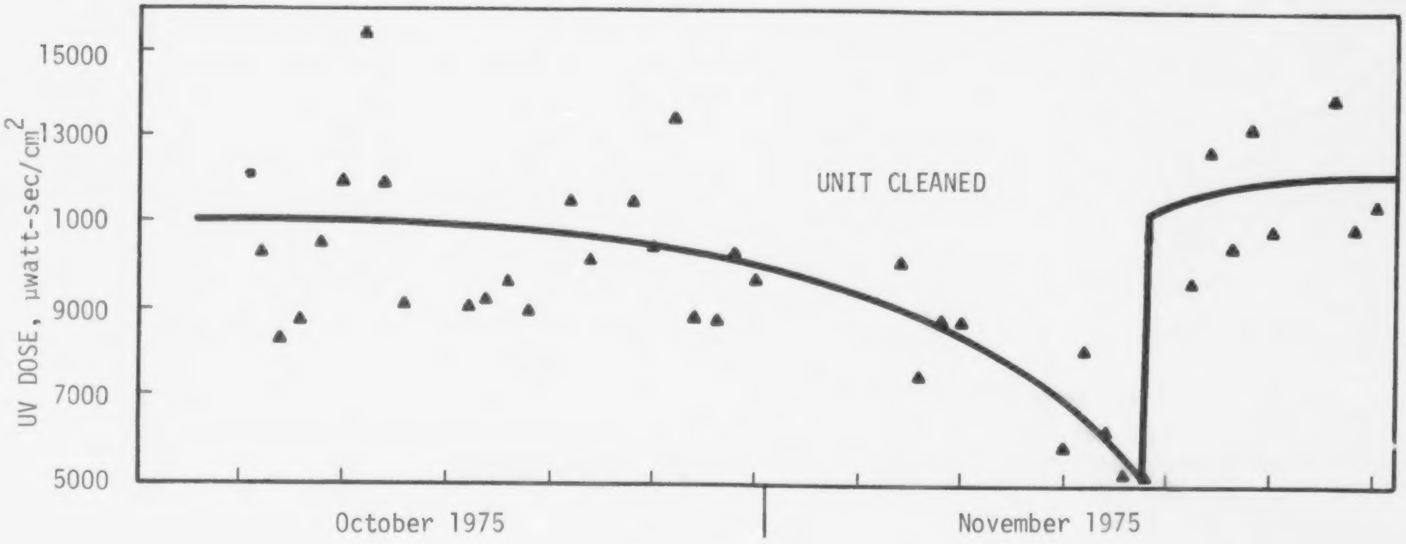


Figure 127. Effect of cleaning the quartz sleeves on UV dose.

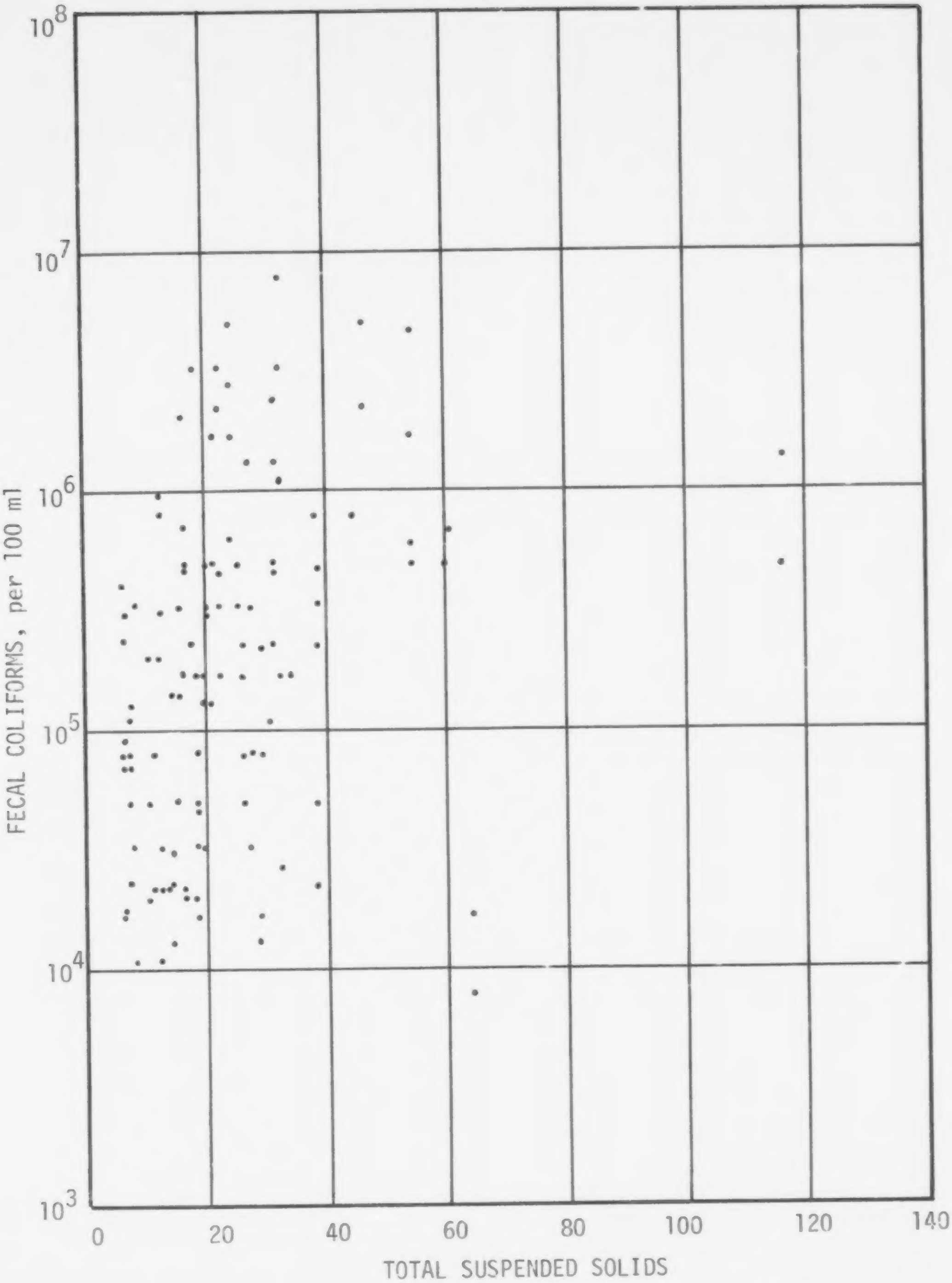


Figure 128. Effluent suspended solids versus effluent fecal coliforms.

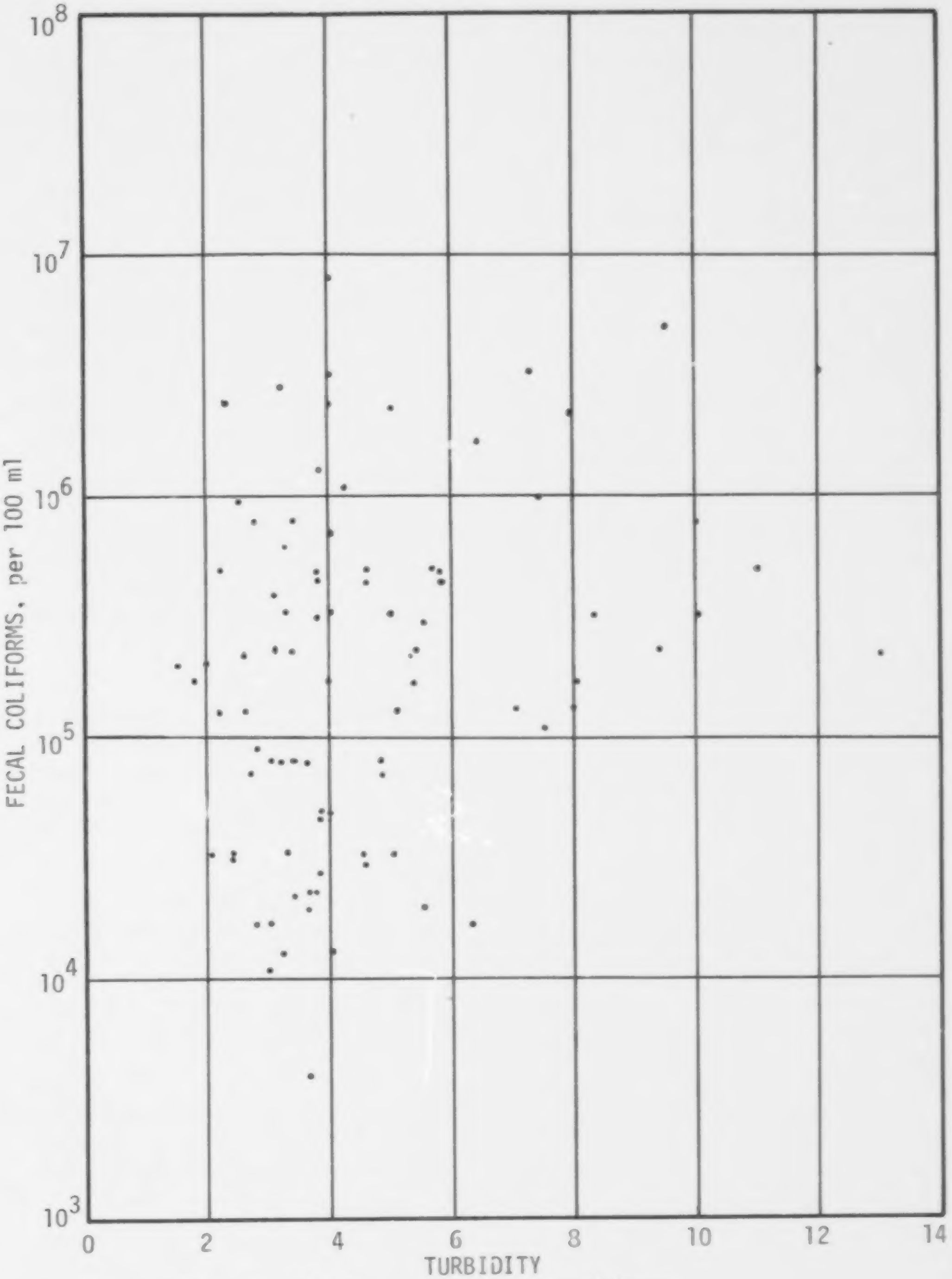


Figure 129. Turbidity versus fecal coliforms.

since the result is contrary to what one intuitively would expect. One must note that the range of turbidity and suspended solids values observed during this project was not great; therefore, this finding cannot be extrapolated to very turbid water, or waters with high suspended sólids concentrations with any degree of confidence. However, the range of TSS concentrations and turbidity values encountered during the project are likely to be typical of municipal secondary treatment plants. And over this range, turbidity and TSS are not particularly important water quality parameters with respect to UV disinfection.

The only practical method that can be used at this time to routinely monitor UV dose is the direct measurement of UV intensity at some point on the wall of the exposure chamber. Two factors should be primarily responsible for changes observed in the measured UV intensity - the light transmissability of the water and slime accumulation on the quartz sleeves. Figure 130 is a plot of measured UV intensity versus percent transmittance. There is no apparent correlation. The graph includes data for ten months, and better results were expected. At this time no reason for the lack of correlation can be offered except for slime growth on the quartz sleeves.

The routine measurement of UV intensity does constitute an excellent process control procedure. Measured UV intensities and observed log reductions in fecal and total coliforms are shown in Figure 131 and 132, respectively. The data plotted are from the ten month period starting on February 1, 1975 and ending November 30, 1975. Visual inspection indicates good correlation.

The number of organisms present in an effluent disinfected with UV light is a function of not only the applied UV dose, but also the number of organisms present in the influent. Data plotted for the individual runs illustrate this point clearly. In particular Figures 99 and 100 show the change in coliform densities in the influent and effluent observed during Run U7.

The singularly most important factor in determining the number of coliform organisms to be found in a UV disinfected effluent is the UV dose. Figure 133 presents a plot of effluent fecal coliforms per 100 ml versus UV dose, and the correlation is good ($r = -0.61$). These data are from Run No. U8, and indicate that if an effluent fecal coliform count of 200 per 100 ml is desired a UV dose of at least 15,500 μwatt - sec per sq. cm. is required.

During the discussion of individual UPS runs two dose values have been reported, the calculated dose, D_T, and the indicated dose, D_I. A least-squares curve fit of the average dose values for each run resulted in the following estimating equation,

$$D_I = 1.27 \times D_T - 5670$$

and the resulting correlation coefficient was 0.83.

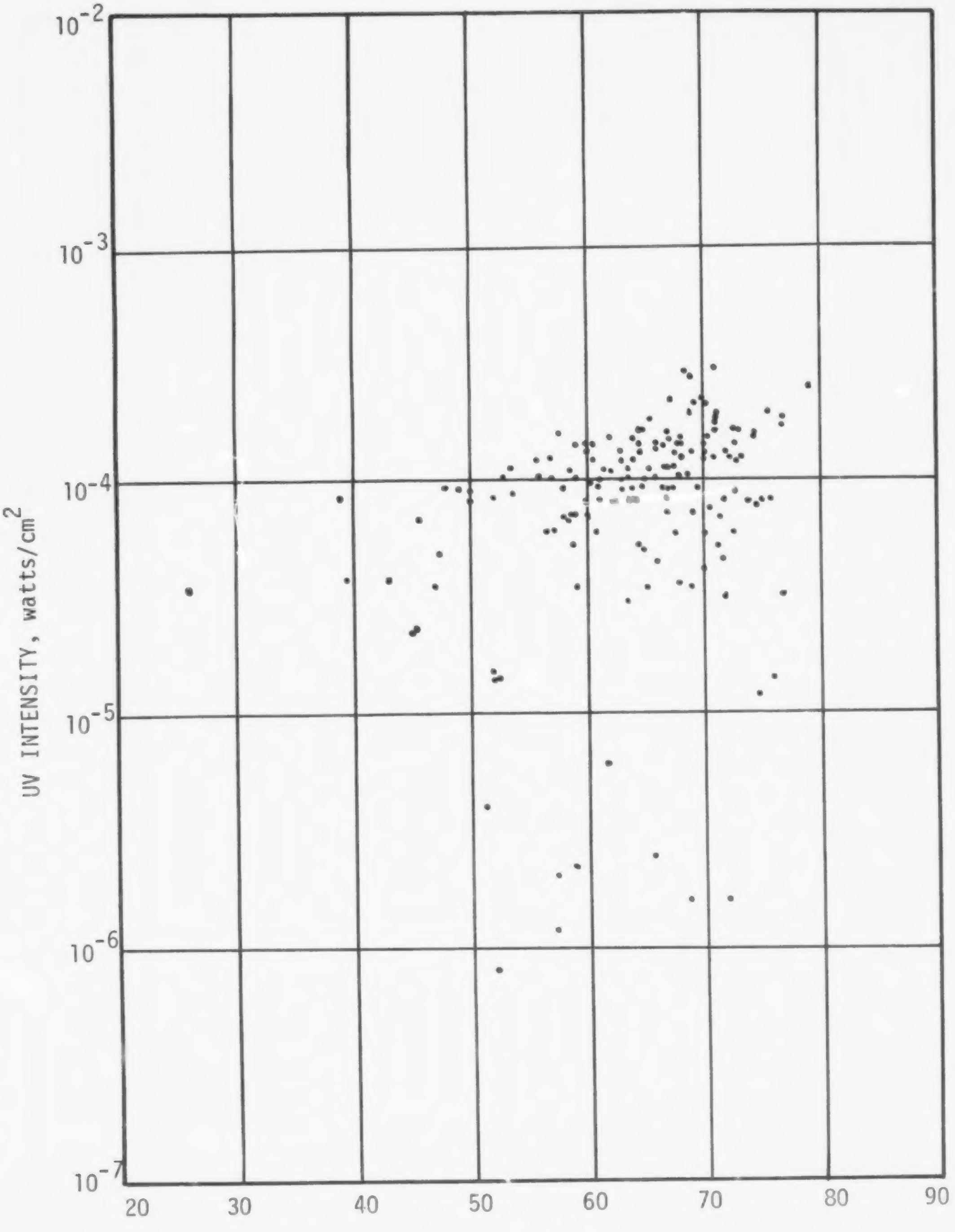


Figure 130. UV intensity versus percent transmittance.

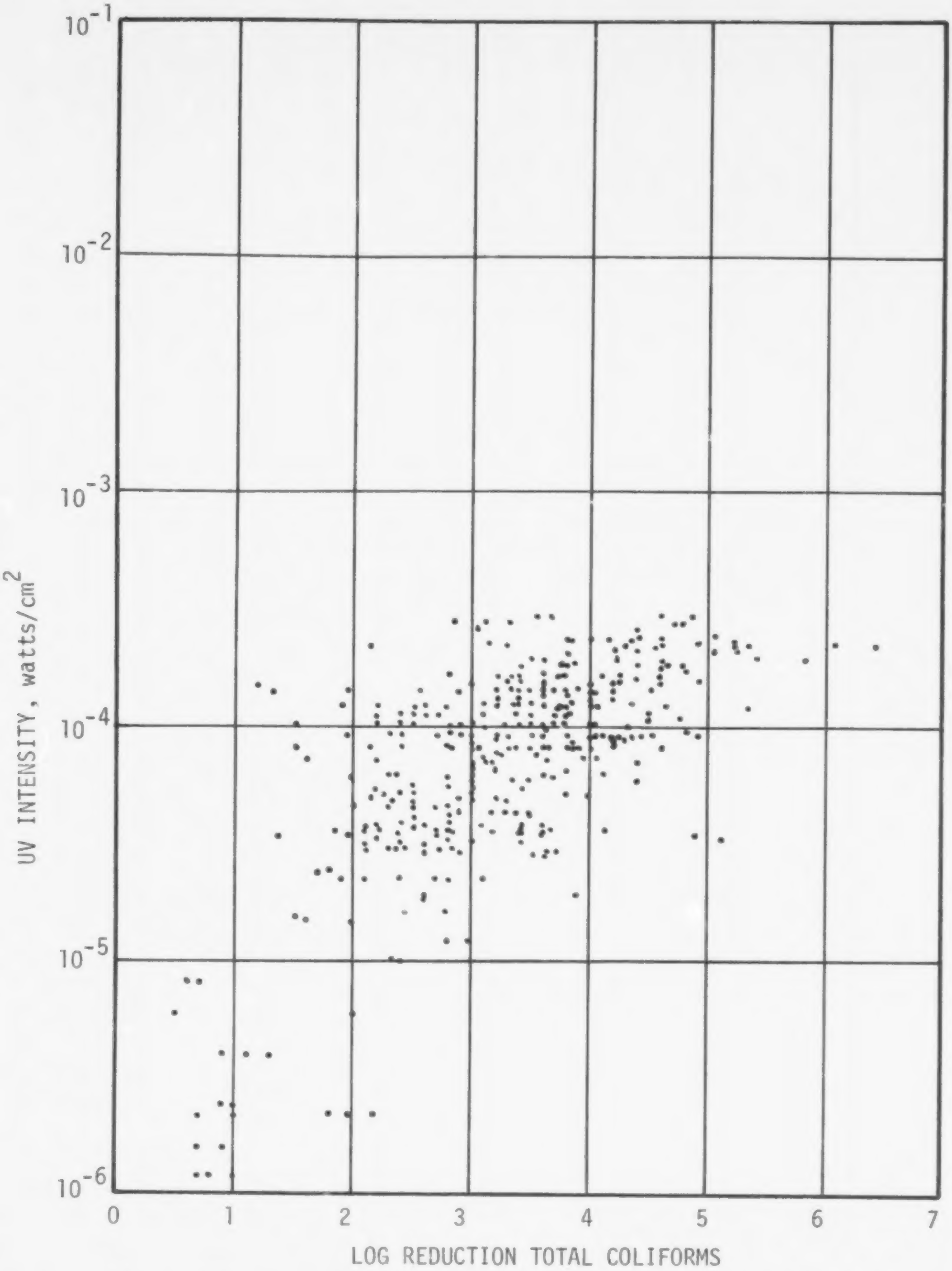


Figure 131. Observed UV intensities versus log reduction in total coliforms.

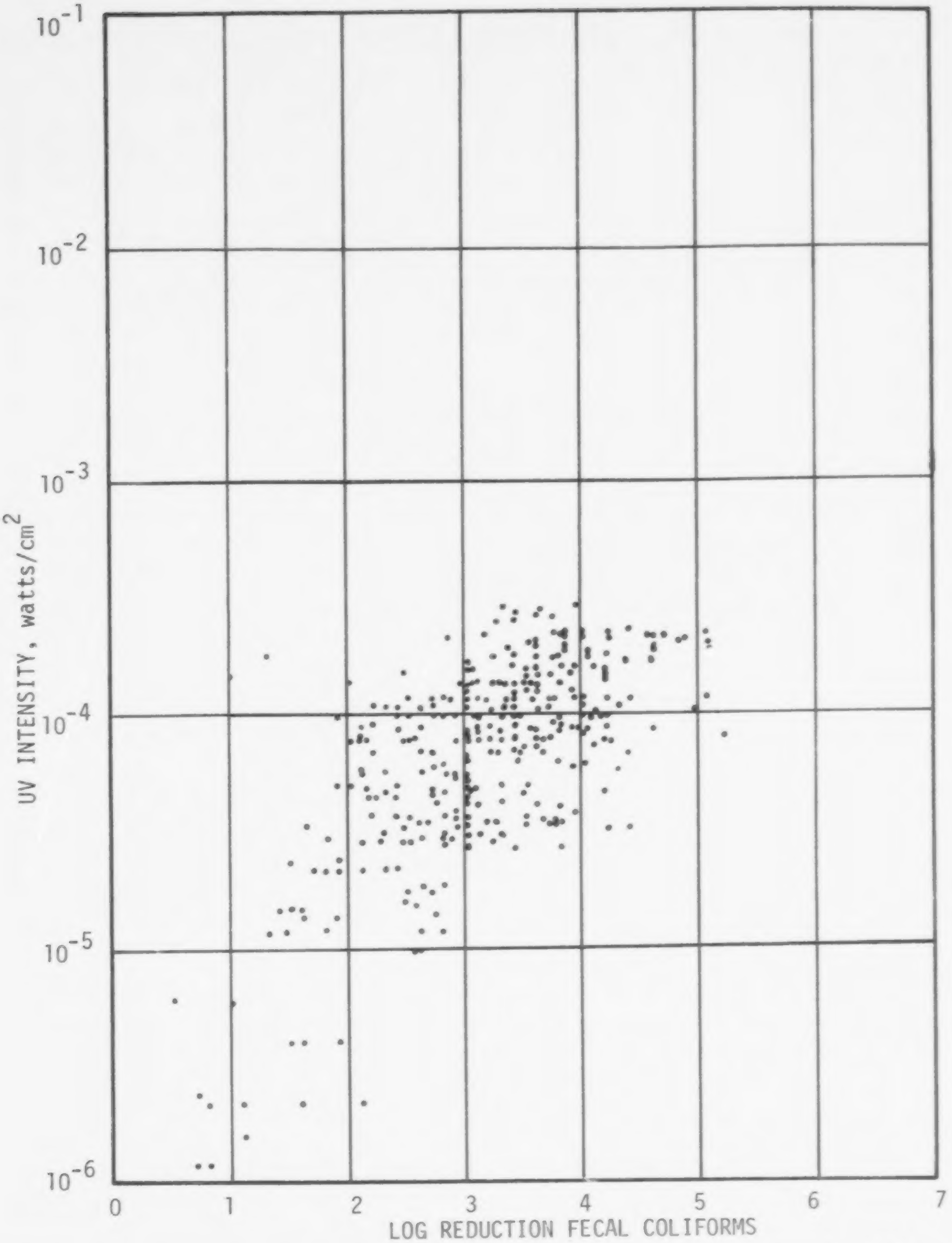


Figure 132. Observed UV intensities versus log reductions in fecal coliforms.

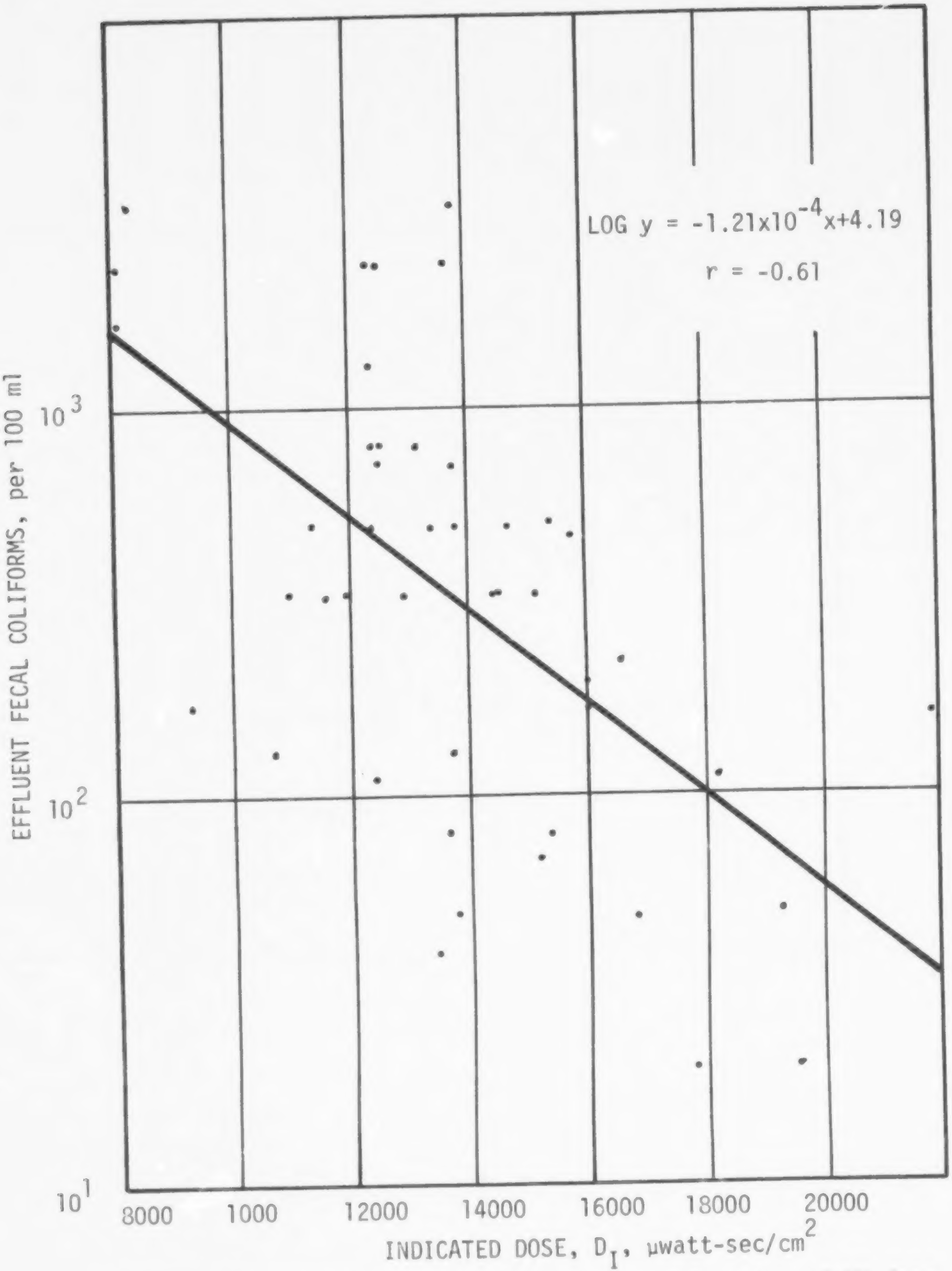


Figure 133. Effluent fecal coliforms as a function of UV dose.

Figure 134 presents two graphs, one of the calculated dose, D_T, versus log reductions in fecal coliforms, the other of indicated dose, D_I, versus log reduction in fecal coliforms. The values plotted are means for each of the UPS runs, and the estimating equations and correlation coefficients are shown with the appropriate graph. Very good correlation was observed ($r = 0.83$ for D_T and 0.86 for D_I) between dose and observed log reduction value.

The same data analyses are presented for the total coliform and dose data in Figure 135. Estimating equations and correlation coefficients are included on the figure. Excellent correlation was observed, especially between the indicated dose, D_I, and the observed log reductions in total coliforms which had a correlation coefficient of 0.96. Both total and fecal coliform log reductions correlated better with the indicated dose than the calculated dose. This is to be expected since the indicated dose is a better indicator of the amount of UV energy actually reaching the organisms.

Figure 136 is a plot of the $\log_{10}$ of the indicated dose, D_I, versus the log of the coliform density whose probability of exceedence is greater than or equal to five percent. The fecal coliform densities were obtained from the extreme value frequency distributions for each of the UPS runs, and the dose values are means for each run. The correlation coefficient is -0.96, which is excellent. The curve indicates that a fecal coliform density of 200/100 ml can be expected to be exceeded five percent of the time if the indicated dose is 24,400 μwatt-sec/cm^2.

Similar analyses with exceedence probabilities of one percent and ten percent using a semi-log form resulted in correlation coefficients of -0.88 and -0.90, respectively.

Table 57 and 58 summarize the data for the Kelly-Purdy unit and the UPS unit respectively. Even a cursory scan of the log-reduction columns will indicate that the UPS unit exhibited vastly superior performance. This should be expected since the UPS unit is a modern design, and several factors contributed to the Kelly-Purdy unit's inadequacy.

The major operational difficulty encountered with the old Kelly-Purdy unit was sludge accumulation in the bottom of the exposure chamber. The chamber functioned as a "shallow-tray" sedimentation basin, and the rate of sludge accumulation was appreciable. As a result of the system geometry, it was possible to take advantage of radiation from only 180 degrees of the lamps in the Kelly-Purdy unit, while emission from the full 360 degrees could be used in the UPS unit, making the UPS configuration more effective.

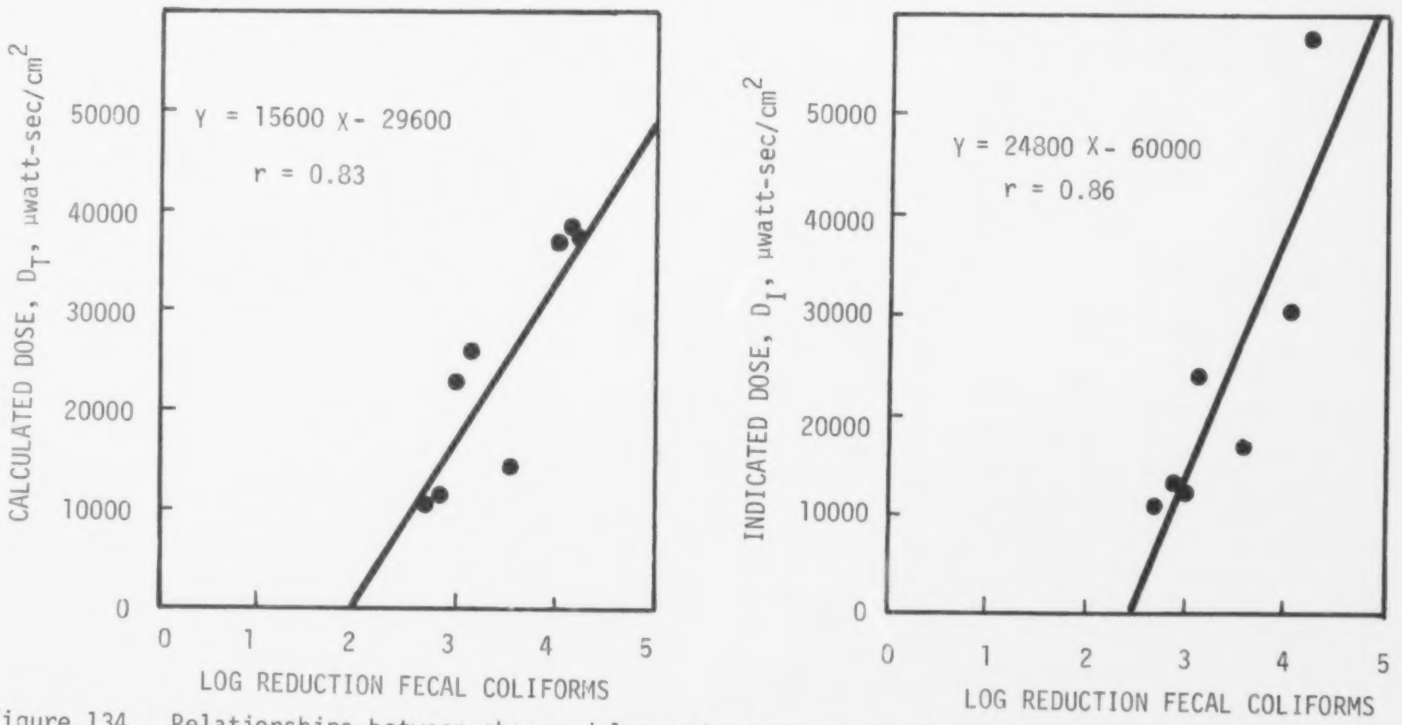


Figure 134. Relationships between observed log reductions in fecal coliforms and the calculated and indicated UV dose.

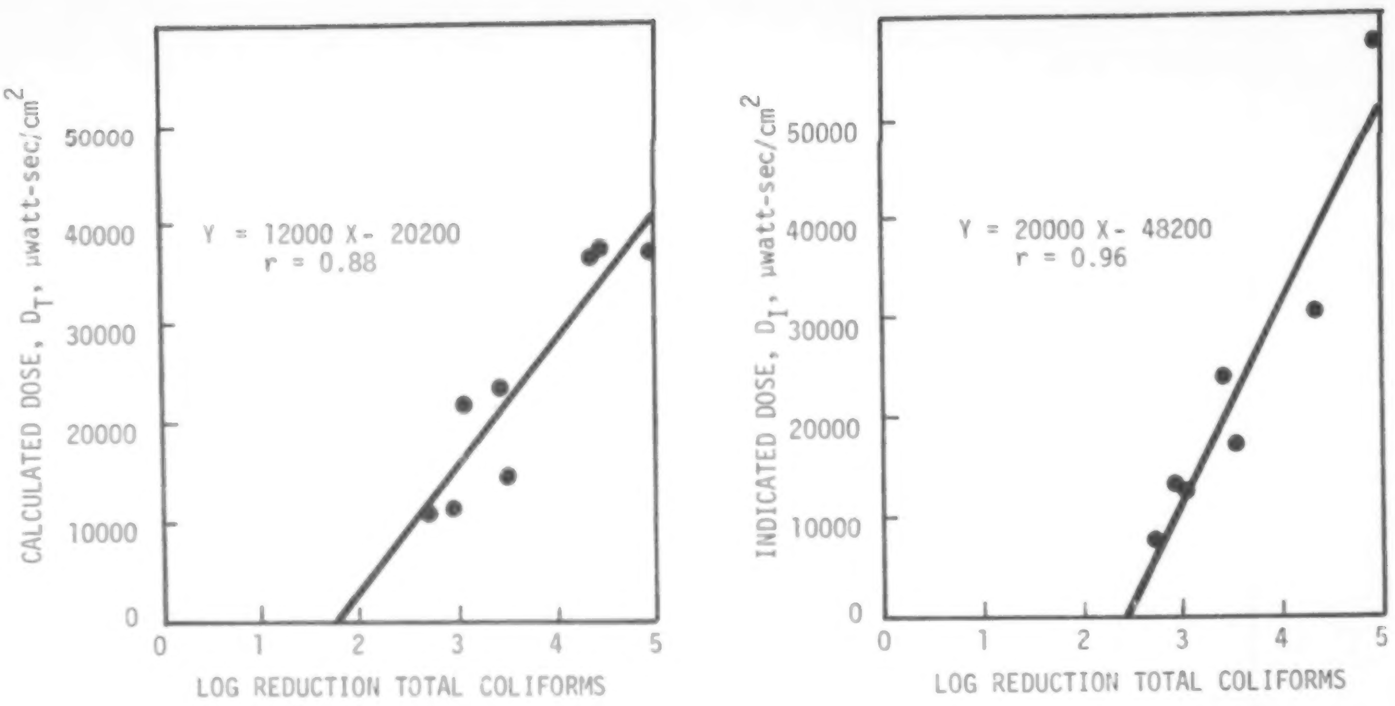


Figure 135. Relationships between observed log reductions in total coliforms and the calculated and observed UV dose.

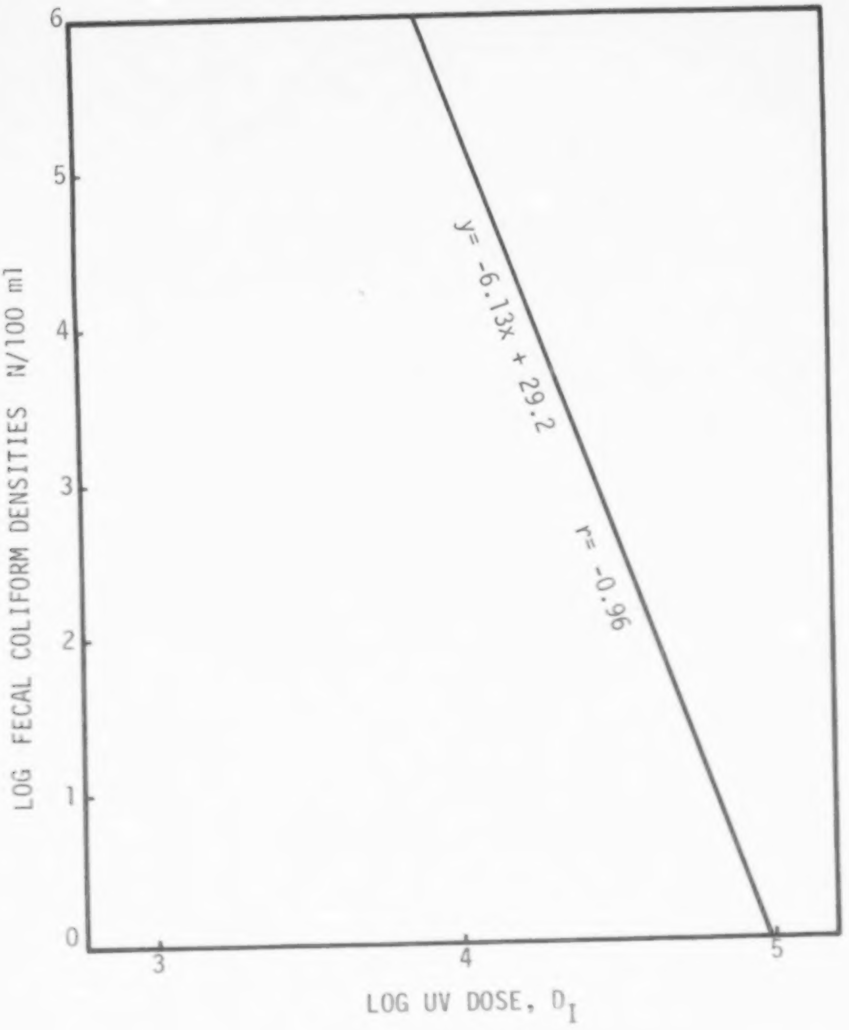


Figure 136. Fecal coliform densities with an exceedence probability greater than or equal to 5 percent versus indicated dose.

TABLE 57. SUMMARY OF THE DATA FOR THE KELLY-PURDY DISINFECTION UNIT.

Run No.	Type of Influent	Extinction Coefficient, k	Theoretical Residence time, sec	Theoretical Dose µwatt-sec/cm^2	Fecal Coliforms per 100 ml Influent	Fecal Coliforms per 100 ml Effluent	Mean Log Reduction	TSS mg/l	INFLUENT COD mg/l	INFLUENT TOC mg/l	TURB. NTU
K1	A.S.E.^{1}	0.5	108	38,800	4.4×10^5	2.4×10^3	2.25	13	-	-	3.7
K2	A.S.E.^{1}	-	-	-	2.3×10^5	2.9×10^2	2.90	7	-	-	3.9
K3	A.S.E.^{1}	0.5	36	24,500	3.8×10^5	3.1×10^2	3.09	26	-	11	8.4
K4	F.A.S.E.^{2}	0.4	43	32,000	5.2×10^4	$<2.1 \times 10^1$	3.40	6.7	14	9	2.6
K5	A.S.E.^{1}	0.55	29	18,800	1.6×10^6	1.6×10^3	3.00	59	92	32	11

[1] Activated sludge effluent.

[2] Filtered activated sludge effluent.

TABLE 58. SUMMARY OF THE DATA FOR THE UPS DISINFECTION UNIT.

Run No.	Type of Influent	Transmittance percent	Theoretical Residence time, sec	Calculated Dose, D_T µwatt-sec/cm^2	Actual Residence time, sec	Indicated Dose, D_I µwatt-sec/cm^2	Fecal Coliforms per 100 ml Influent	Fecal Coliforms per 100 ml Effluent	Log Reduction	Inf COD mg/l	Inf TSS mg/l	Inf TOC mg/l	Inf NH_3-N mg/l
U1	A.S.E.^{1}	70.7	29.8	37,200	28	-	3.7×10^4	$<2.3 \times 10^0$	>4.21	17	7	6	2.2
U2	A.S.E.^{1}	71.8	28.2	36,600	25	30,500	3.4×10^4	$<3.1 \times 10^0$	>4.04	22	42	<6	1.8
U3	F.A.S.E.^{2}	68.9	33.5	37,100	29.5	57,800	3.3×10^4	$<2.0 \times 10^0$	>4.22	18	2	8	1.1
U4	C.A.S.E.^{3}	66.2	27.5	25,900	24.5	24,000	6.0×10^3	$<4.3 \times 10^0$	>3.15	19	6	9	0.8
U5	A.S.E.^{1}	68.4	21.5	22,800	19.5	12,300	$>2.9 \times 10^5$	$>2.8 \times 10^2$	3.01	44	27	11	7.1
U6	F.A.S.E.^{2}	54.1	24.4	10,800	22	7,640	9.8×10^5	$<2.0 \times 10^3$	>2.69	55	19	17	12.6
U7	F.A.S.E.^{2}	64.1	17.3	14,500	15.5	17,000	$<3.7 \times 10^5$	$<1.0 \times 10^2$	3.57	26	4	12	4.0
U8	A.S.E.^{1}	61.2	16.8	11,500	15.0	13,400	$<2.9 \times 10^5$	$<4.2 \times 10^2$	2.84	37	13	12	5.4

[1] Activated sludge effluent.

[2] Filtered activated sludge effluent.

[3] Chemically treated activated sludge effluent.

SECTION 10

PHOTOREACTIVATION

In October 1974, a photoreactivation study was performed using clear and amber glass sample bottles. The results indicated that exposure of UV effluent samples to 30 minutes of sunlight produced a 1.1 log rise in total coliforms, and a 0.6 log rise in fecal coliforms.

A study was conducted during August 1975 to see if similar observations could be made on a pilot scale. The plant's two chlorine basins, into which the UV unit normally discharged, were set up to operate in parallel. A wooden frame covered with a black poly-vinyl chloride (PVC) sheet was constructed and placed over the No. 2 chlorine basin to black out sunlight. The No. 1 basin remained open to the atmosphere. In this manner, UV effluent was split continuously to an open and a covered basin. No chlorine was fed during this period. Figure 137 shows the arrangement of the Demonstration Plant during this special 20-day study, which ran from 1 to 19 August 1975. Although this period overlapped two UV runs, the operation of the UV exposure chamber was not altered for this study.

Table 59 outlines the major operating parameters of interest. Half the flow from the UV contactor entered the No. 1 (open) basin, while the other half entered the No. 2 (covered) basin. At flows of 1.5 l/sec, each basin had a theoretical detention time of 65 minutes. Previous dye tests indicated the actual time to be very close to theoretical. It was assumed that half of the irradiated effluent was subjected to 65 minutes of sunlight, the other half to 65 minutes of darkness.

Samples of the effluent from each basin were collected over the 20-day study period in coordination with the normal UV sampling program. In this manner UV effluent samples corresponded to the influent of both basins. All light-dark samples were collected in dark glass sample bottles. Samples were taken only during daylight hours. It became evident after several days that algae were present in both basins, although much more so in the open (light) basin than in the covered one. The covered basin was not truly dark as originally intended because a small amount of light seeped around the edges of the cover.

A chemical and bacteriological summary of the light-dark sampling appears on Table 60. Bacteriological data are reported as geometric means. Substantial increases in MPN's occurred in both basins, although the basin exposed to sunlight showed a larger increase. Total coliforms increased 0.7 log in the light basin, but only 0.3 log in the dark basin. Likewise,

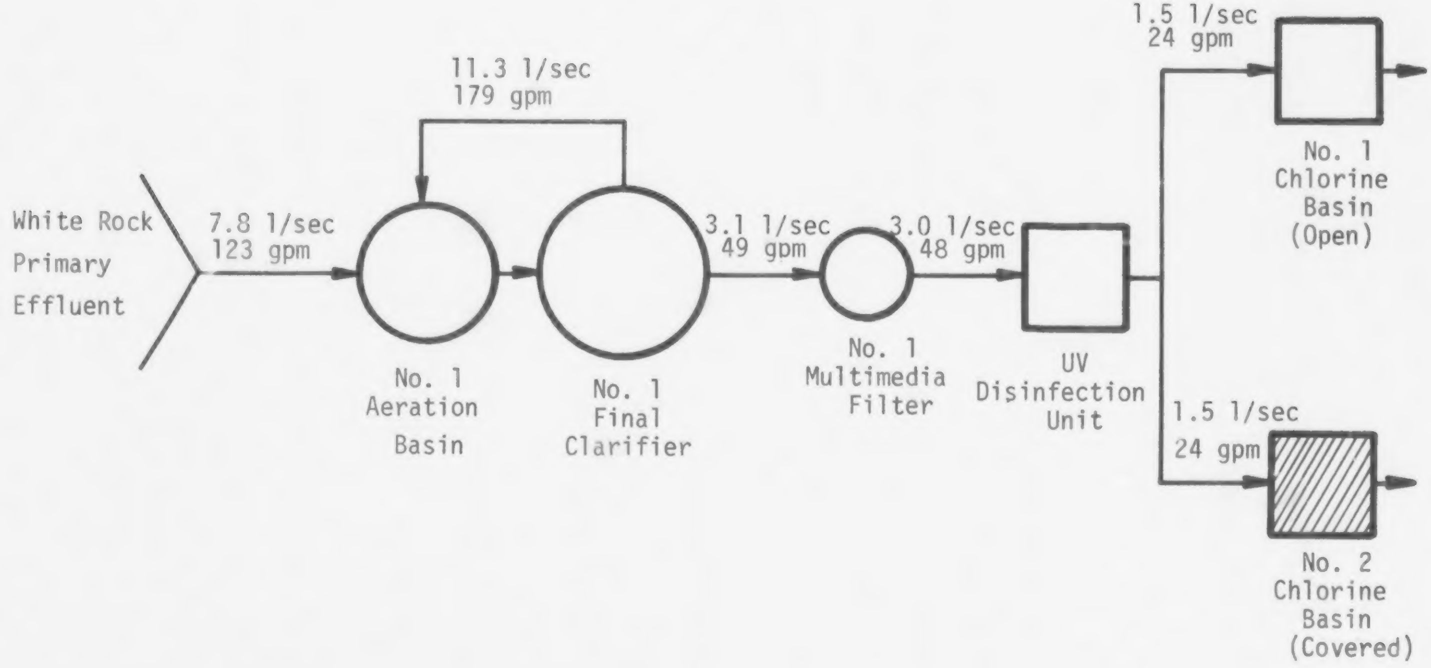

White Rock
Primary
Effluent
7.8 l/sec
123 gpm
11.3 l/sec
179 gpm
No. 1
Aeration
Basin
No. 1
Final
Clarifier
3.1 l/sec
49 gpm
No. 1
Multimedia
Filter
3.0 l/sec
48 gpm
UV
Disinfection
Unit
1.5 l/sec
24 gpm
No. 1
Chlorine
Basin
(Open)
1.5 l/sec
24 gpm
No. 2
Chlorine
Basin
(Covered)

Figure 137. Process configuration for light-dark study: August 1-19, 1975.

TABLE 59. PROCESS CONTROL AND OPERATION SUMMARY LIGHT-DARK STUDY: AUGUST 1-19, 1975

UV DISINFECTION UNIT	
Flow	3.0 l/sec
Theoretical detention time	18 sec.
Water temperature	28 degrees C
UV intensity	122 μwatts/cm^2
Water quality	Out of Service
Transmittance (@2537 A^o)	63.3 percent
NO. 1 CHLORINE BASIN	
Flow	1.5 l/sec
Theoretical detention time	65 minutes
Conditions:	Open to atmosphere
NO. 2 CHLORINE BASIN	
Flow	1.5 l/sec
Theoretical detention time	65 minutes
Conditions:	Surface covered

TABLE 6Q. CHEMICAL AND BACTERIOLOGICAL SUMMARY OF THE LIGHT-DARK STUDY, AUGUST 1-19, 1975

PARAMETER	INFLUENT (UV EFF) (N)	LIGHT (OPEN) (N)	DARK (COVERED) (N)
Total MPN*	4,600 (11)	21,000 (13)	9,300 (15)
Fecal MPN*	370 (9)	3,800 (15)	2,000 (15)
DO, mg/l	1.1 (15)	1.9 (15)	1.7 (15)
Color	23 (15)	28 (15)	27 (15)
Turbidity, FTU	1.3 (12)	1.3 (8)	1.1 (8)
TSS, mg/l	6 (14)	17 (15)	17 (15)
VSS, mg/l	4 (13)	14 (14)	16 (13)
BOD_5, mg/l	2.3 (12)	5 (12)	5 (13)
COD, mg/l	28.8 (14)	45.4 (15)	42.8 (15)
TOC, mg/l	13 (14)	13 (15)	14 (15)
pH	7.4 (15)	7.3 (14)	7.3 (14)

*Geometric Mean

fecal coliforms increased by 1.0 log and 0.7 log in the light and dark basins, respectively. The increases in D.O., VSS, and COD are indicative of the algal masses which were present in each basin.

Figure 138 is a time-series plot of fecal coliform populations in the: a) influent (solid line), b) open basin effluent (broken line), and c) covered basin effluent (dotted line). In general, both basin effluents had higher MPN's than the influent, and the coliform densities in the open basin were consistently higher than the covered basin. (The gap from 4 August through 8 represents down-time for installation of new aeration equipment in the No. 1 aeration basin). Figure 139 is a plot of the paired fecal coliform populations in the open and covered basins. Clearly, the open basin had higher population in 10 out of 14 samples.

A two-tailed t-test (15) was used to compare the log mean coliform values between sampling points. Under the null hypothesis, $H_0 : \mu_1 = \mu_2$, where μ_1 and μ_2 are the population means being compared, the t-statistic is calculated as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sigma\sqrt{1/N_1 + 1/N_2}}, \text{ where}$$

$$\sigma = \sqrt{\frac{N_1 s_1^2 + N_2 s_2^2}{N_1 + N_2 - 2}}$$

$\bar{X}_1$ = first sample mean with N_1 data points,

$\bar{X}_2$ = second sample mean with N_2 data points,

s = sample standard deviation

σ = population standard deviation

A significance level of 0.05 was chosen to test the hypothesis. Results are presented in Table 61. It is evident that two of the six tests failed the null hypothesis, i.e., log influent total coliforms were significantly different from log open basin total coliforms. All other differences were not statistically significant. Thus, increases in total coliform numbers likely occurred in both basins, but the increases could not be attributed to photoreactivation *per se*. It should be emphasized, however, that sample sizes were relatively small and that a considerably different conclusion may have resulted if larger sample sizes had been used. Furthermore, since the covered basin was not completely opaque to visible light, some of the increase in coliform numbers in the covered basin may still have been due to photoreactivation.

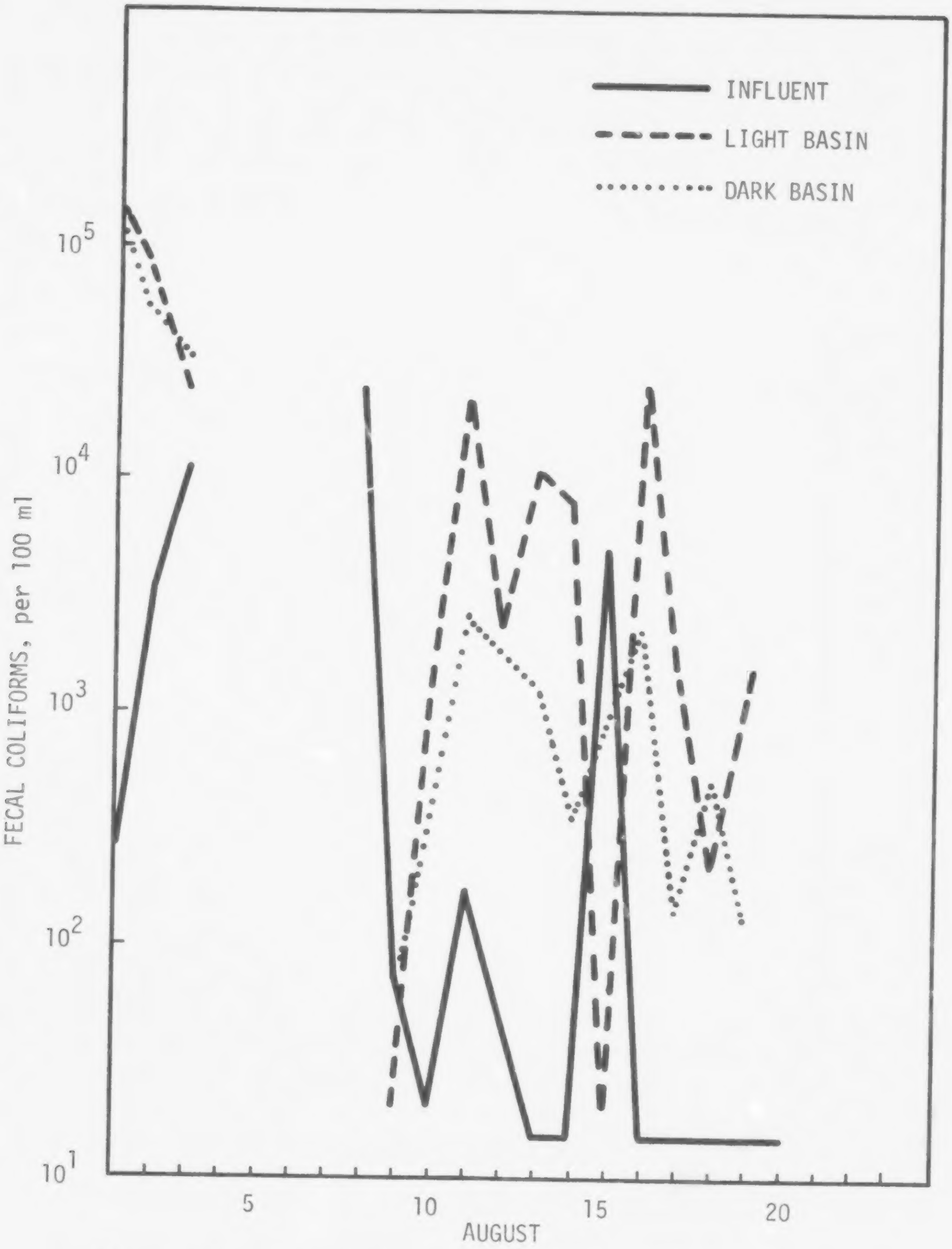


Figure 138. Time-series plots of fecal coliform data for the light dark study.

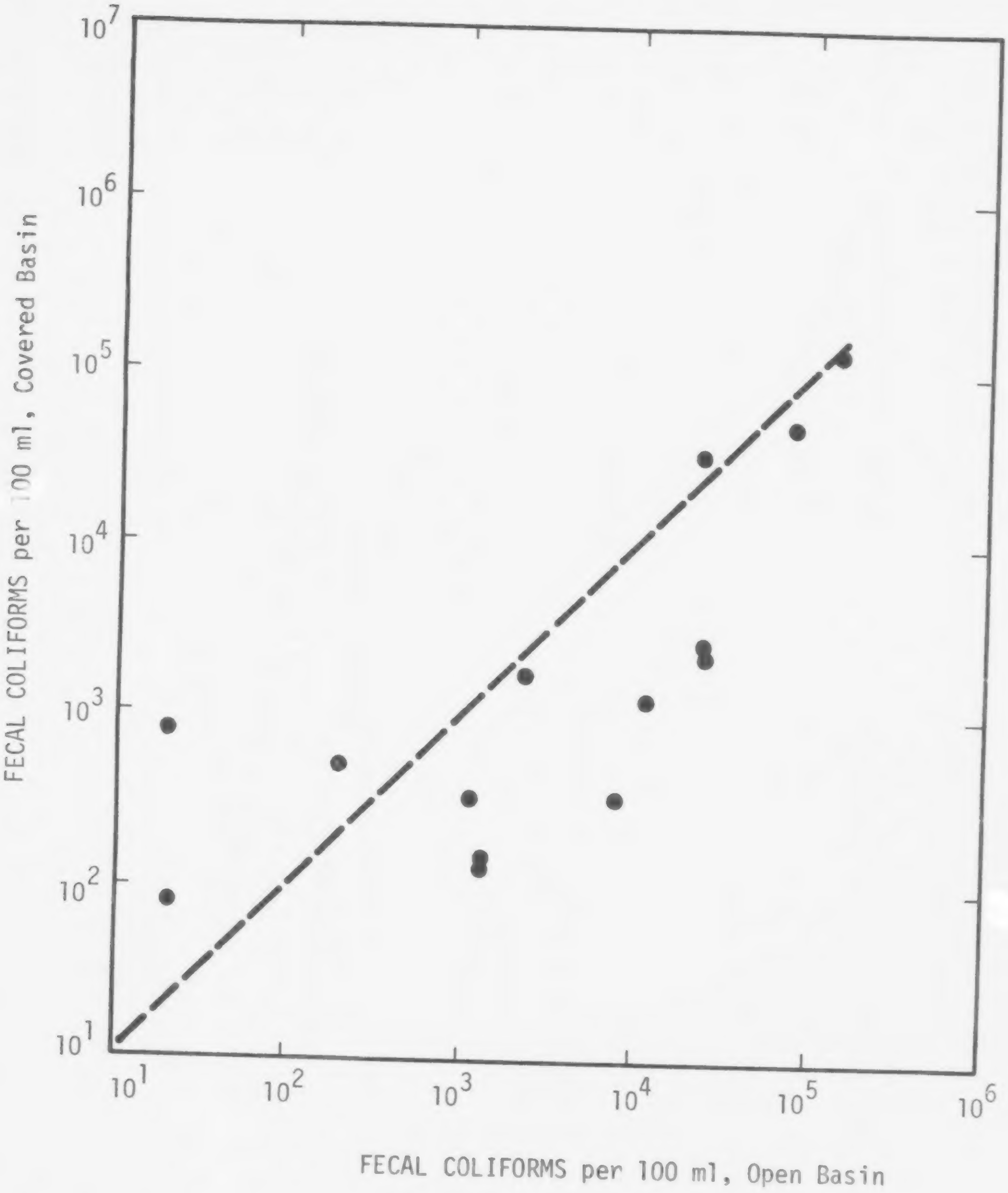


Figure 139. Fecal coliforms in open basin versus covered basin.

TABLE 61. ANALYSIS OF MEAN COLIFORM DENSITIES IN LIGHT-DARK STUDY

	Log Mean Coliform Density							
Parameter	n	Influent	n	Covered	n	Open	Std. Dev.	t
Total	11	2.66	15	3.97			1.08	3.05*
Coliforms	11	2.66			13	4.31	1.18	3.43*
			15	3.97	13	4.31	1.09	0.91
Fecal	9	2.57	15	3.29			1.15	1.48
Coliforms	9	2.57			15	3.58	1.25	1.92
			15	3.29	15	3.58	1.22	0.66

*Significant at 95% level.

REFERENCES

1. Wolf, H.W. and S.E. Esmond. Water Quality for Potable Reuse of Wastewater. Water and Sewage Works, 121 (2): 48, 1974.

2. Wastewater Reclamation Studies in Dallas, Texas, Final Report on Project No. 17080 EKG, Dallas Water Utilities Department and Texas A&M Research Foundation, March 1973.

3. Research and Development Division Projects Receiving Federal Assistance, 1969-1976, Report to the Director, Dallas Water Utilities, 1976.

4. Wolf, H.W., R.S. Safferman, A.R. Mixson, and C.E. Stringer. Virus Inactivation during Tertiary Treatment. Virus Survival in Water and Wastewater Systems, J.F. Malina Jr. and B.P. Sagik, Ed. Center for Research in Water Resources, The University of Texas at Austin (1974).

5. Petrasek, A.C., Jr. Wastewater Characterization and Process Reliability for Potable Wastewater Reclamation. EPA-600/2-77-210, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977, 114pp.

6. Standard Methods for the Examination of Water and Wastewater, 13th ed., American Public Health Assoc., Inc., Washington, D.C., 1971.

7. Morrill, A.B. Sedimentation Basin Research and Design. American Water Works Association Journal, 24 (9): 1442-1463, 1932.

8. Thomas, H.A., Jr. and R.S. Archibald. Longitudinal Mixing Measured by Radioactive Tracers. Transactions of the American Society of Civil Engineers, 117:839-855, 1952.

9. Gumbel, E.J. Statistics of Extremes. Columbia University Press, New York, 1958.

10. Benjamin, J.R. and C.A. Cornell. Probability,Statistics, and Decision for Civil Engineers. McGraw-Hill Book Company, New York, 1970.

11. Parker, C.A. A New Sensitive Chemical Actinometer, I. Some Trials with Potassium Ferioxylate. Proc. of the Royal Society of London, A220:104-116, 1953.

12. Calvert, J.G. and J.N. Pitts Jr. Photochemistry. John Wiley and Sons, Inc., New York, 1967. pp 780-813.

REFERENCES (continued)

13. Roeber, J.A. and F.M. Hoot. Ultraviolet Disinfection of Activated Sludge Effluent Discharging to Shellfish Waters, EPA-600/2-75-060, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1975. 85 pp.

14. Witherell, L.E., R. Solomon, and K.M. Stone. A Demonstration Project to Determine the Feasibility of Using Ozone and Ultraviolet Radiation Disinfection for Small Community Water Systems. In: Proceedings of AWWA Disinfection Seminar, American Water Works Association, Anaheim, California, 1977.

15. Spiegel, Murray R. Schaum's Outline of Theory and Problem of Statistics. McGraw-Hill Book Company, New York, 1961.